Eco-decision Making for Pavement Construction Projects

Yen-Yu Lin

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Reading Committee:
Stephen T. Muench, Chair
Joe P. Mahoney
Linda T. Boyle

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University of Washington

Abstract

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Yen-Yu Lin

Chair of the Supervisory Committee:
Associate Professor Stephen T. Muench
Department of Civil and Environmental Engineering

Life cycle assessment (LCA) is a promising approach that can be used to quantify environmental impacts for selected products within defined system boundaries. Although LCA has begun to be applied to pavement systems, the practice is in its infancy and, as yet, rather ill-defined. Existing pavement LCAs methods and tools are not adequate or consistent in terms of system boundary, data quality, and transparency. Currently, it is not practical to expect pavement practitioners to conduct their own LCAs because of the specialized knowledge and extensive time required. However, an appropriate LCA software tool, intended for use by pavement practitioners, could assist in performing LCAs and allow pavement LCA to become a low-cost standard practice capable of providing valuable accounting and decision support.

This research established an LCA framework and a robust data inventory for pavement LCA that is both deterministic and probabilistic. An Excel-based tool, Roadprint, was developed for this proposed framework and data inventory. This tool can facilitate knowledge that will (1) implement pavement LCA in a standardized and reproducible manner, (2) conduct probabilistic analysis, and (3) generate well-analyzed presentations of results to interpret LCA outputs.

Raodprint was assessed using six standard pavement designs, three case studies, and four other pavement LCA tools. This assessment showed:

- Roadprint is capable of differentiating various parameters, to delineate projects conditions, and it is superior to other tools in terms of scope, system boundary, and data quality.
- Improving the material production processes would be the most effective way to mitigate overall environmental impacts of pavement construction.
- Users of LCA results should be aware of whether feedstock energy is included in the result, because it can increase reported energy consumption two to threefold.
- Comparisons results from different LCA tools can be misleading because the differences in tools could overwhelm the differences in actual processes.
- It is essential to match the scope, system boundary, and data quality of the LCA tool being used to the goal of an LCA comparison or accounting.

In summary, Roadprint can help researchers, policy makers, and engineers make better decisions prior to the implementation of environment-significant and costly pavement projects.

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LIST OF ACRONYMS AND ABBREVIATIONS

BenReMod	Beneficial Reuse Modules
BFS	Blast Furnace Slag
CIR	Cold In-place Recycling
CSOL	Crack, Seat, and Overlay
DBR	Dowel Bar Retrofit
EIA	Environmental Impact Assessment
EIO-LCA	Economic Input-Output Life-Cycle Assessment
ESAL	Equivalent Single Axle Loads
FA	Fly Ash
FRED	Framework for Responsible Environmental Decision
GHG	Greenhouse Gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	Global Warming Potential
HMA	Hot-Mix Asphalt
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IVL	Swedish Environmental Research Institute Ltd
LCA	Life-Cycle Assessment
LCCA	Life-Cycle Cost Analysis
LCI	Life-Cycle Inventory
LCIA	Life-Cycle Impact Assessment
MTV	Material Transfer Vehicle
OASIS	Operation for Safe, Intelligent, and Sustainable Motorways
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
PCA	Portland Cement Association
PCC	Portland Cement Concrete
PLCA	Process-based Life-cycle Assessment
RAP	Recycled Asphalt Pavement
ROAD-RES	Road Construction and Residue Disposal
SAIC	Scientific Applications International Corporation
SETAC	Society of Environmental Toxicology and Chemistry
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
UCPRC	University of California Pavement Research Center
VTT	Technical Research Centre of Finland

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DEDICATION

I dedicate this dissertation to my dearest grandfather and grandmother.
Both of you are deep in my heart.

Chapter 1. Introduction

1.1 Background

Human beings rely on nature and the earth. For most activities, human beings consume natural resource, such as driving (fuel or diesel), construction (wood, aggregate, steel), and even cooking (electricity or propane). Meanwhile, consuming resources also results in generating environmental burdens that change the ecosystems in an unsustainable way. The Millennium Ecosystem Assessment (United Nation, 2005) found that: (1) over the past 50 years the ecosystems have been changed by humans rapidly and extensively, largely to meet the growing demands for resources from increased populations and industrialization; (2) substantial net gains in human well-being and economic development actually cost degradation and nonlinear changes of ecosystems; (3) the degradation of ecosystems could grow significantly worse in the first half of this century; (4) the challenges of reversing the degradation of ecosystems while meeting increasing demands can be partially achieved by changes in policies, institutes, and current practices.

One example of how humans affect the ecosystems is the use of fossil fuels. Human's demand for fossil increased dramatically in past decades, and the use of fossil fuel creates substantial amounts of emissions. CO_2 is considered a major contributor to climate change, which affects nearly all ecosystems (IPCC, 2007; CDIAC, 2009). As can be seen in Figure 1 the concentration of carbon dioxide (CO_2) follows the use of fossil fuels very closely. Another example is the depletion of natural resources. The 1960s showed a marked increase in industrial and construction materials consumptions in the U.S. (see Figure 2). This negatively changes the ecosystems since the recovery of raw materials can no longer meet the competing demands for the resources.

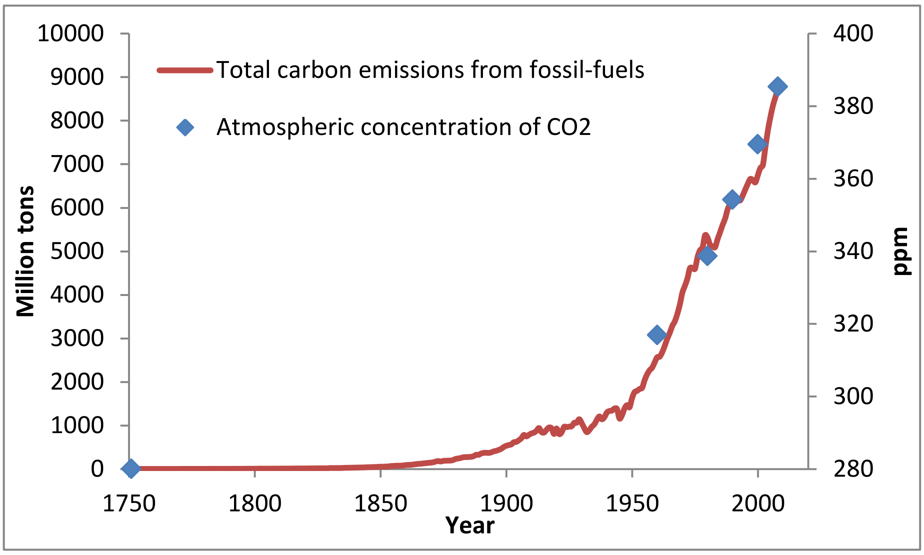


Figure 1 Concentration of carbon dioxide (IPCC, 2007; CDIAC, 2009)

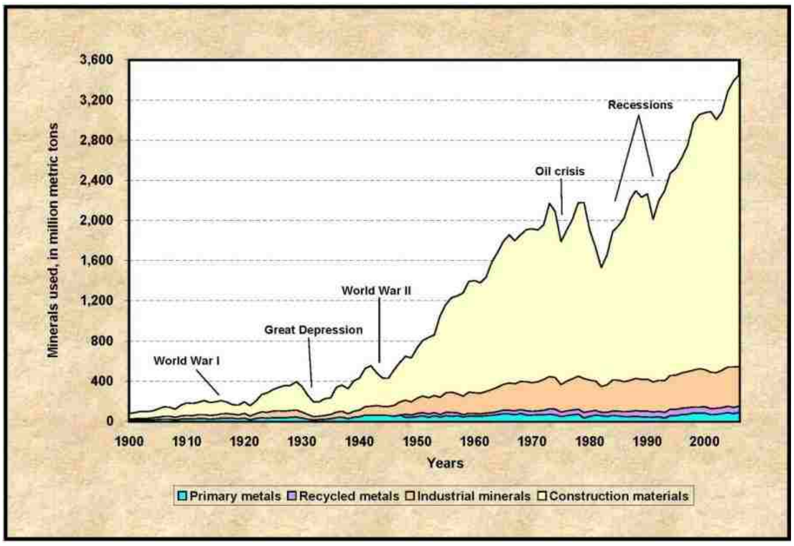


Figure 2 Raw materials consumed in the U.S., 1900 to 2006 (USGS, 2009)

Since man-made environmental impacts have led to increased concerns about environmental protection and conservation, humans have taken some actions. There are policies and standards in place to address various environmental issues, e.g., the Fish and Wildlife Act (1956), the Clean Air Act (1970), and the National Environmental Protection Act (NEPA) (CEQ, 2007). There are other efforts related to ecosystems protection. For example, 38 states in the U.S. have developed policies or regulations about climate change (PEW, 2009) and 24 states have further set targets for greenhouse gases (GHG) reduction. These state governments have advocated and promoted ideas that correspond to actions in every state agency.

1.2 Problem statement

Construction is another human activity that affects the ecosystems, with road-oriented construction plays a significant role. Road-oriented construction accounted for about 70% of projects spending (US Census Bureau, 2010), and the value of the construction is projected to be 150 billion during 2012 (US Census Bureau, 2012) and total employment in this classification was 297,090 (US BLS, 2011). At present, there are $12.08 billion dollars dedicated to pavement improvement, widening, and new construction, under the American Recovery and Reinvestment Act, (GAO, 2009).

Pavement construction has heavy demands for raw materials with approximately 350 million tons of raw materials used per year (Holtz and Eighmy, 2000). Transportation of materials and equipment operations can also generate undesirable impacts to the ecosystems during pavement construction. In summary, pavement construction involves numerous economic activities, a large number of people, and substantial natural resources and the implications to the ecosystems simply cannot be ignored.

To ameliorate the enormous environmental impacts caused by pavement projects, people have been seeking concepts and methodologies to evaluate the environmental impacts of pavement construction projects to make them more efficient and environmentally friendly. In accordance with environmental laws and regulation, such as the NEPA, pavement construction planning is driven by cost efficiency and economics, as well as the environmental impacts.

Environmental impact assessments are often based on subjective and qualitative evaluations, rather than assessments of scientific and quantitative approaches. The presence of quantitative performance measurements to infrastructure and pavement construction projects will be useful by offering more objective evaluations of environmental impacts, to better support the concept of sustainability.

1.3 General significance

Life cycle assessment (LCA) is a well-developed and widely used approach to measure an object's environmental outputs and impacts through its entire life cycle (SETAC, 1991; ISO, 2006). LCA is capable of supporting decision making with quantitative evaluations of in-scope environmental impacts.

There are also voluntary efforts with respect to environmental evaluations that go beyond regulatory minimums. As an example, Figure 3 shows the states participating in a GHG registry or reporting scheme and those states with actual GHG emissions targets. In situations where GHG reporting and reductions in effect, measurement of such emissions, for pavement construction and other efforts, is necessary. LCA can serve as one of the measuring methods.

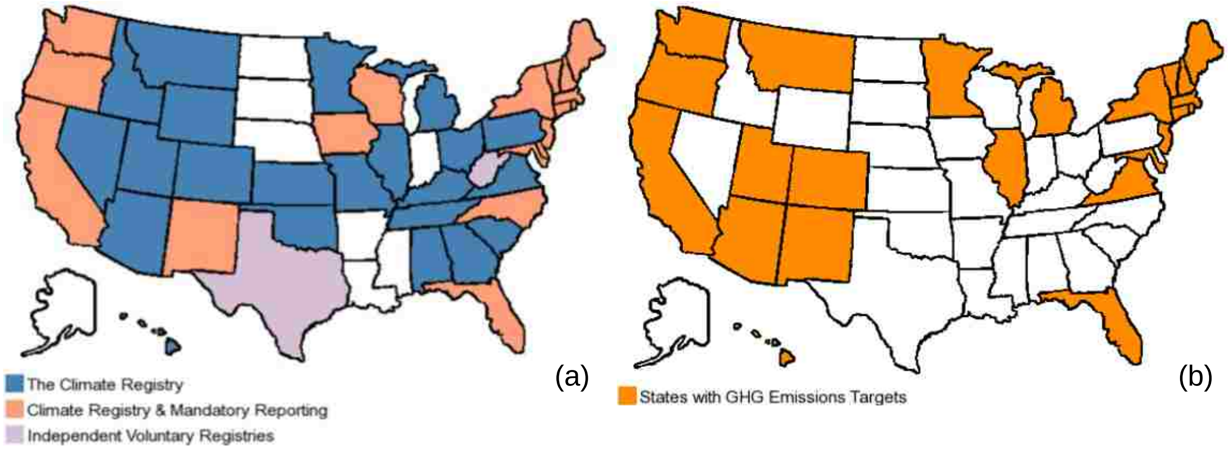


Figure 3 (a) States participate in GHG Registry/reporting; (b) States with GHG emissions targets (C2ES, 2012)

LCA can be used as a supporting tool, for comparing different alternatives during decision-making processes. LCA has been used to compare vehicle emissions between roundabout and signalized intersection with outcomes showing roundabout has lower gasoline consumptions as well as CO2 emissions (Redington, 2001; Alisoglu, 2010). LCA can also be applied on larger scale infrastructure, such as comparison among high-speed rail, heavy rail transit, automobile, and aircraft (Chester and Horvath, 2010).

In Europe, LCA has been used as a research tool in pavement construction since the 1990s (Stripple, 1995; Häkkinen and Mäkelä, 1996; Mroueh et al, 1999), and is sometimes used as a project evaluation tool. Research in the U.S. on the application of LCA methods to pavement construction has also begun (Horvath and Hendrickson, 1998; Horvath, 2003; Zapata and Gambatese, 2005). However, applying LCA methods to pavements is likely to require significant time and expense because (1) conducting a LCA requires expertise not possessed by agencies or road engineers, and (2) currently there is no generally accepted method and user-friendly tool available for use by non-experts. Another issue is valid U.S. data to identify some of the economic and environmental processes related to pavement projects, to generate more reliable results and cross validation.

Based on the previous research on environmental impacts of pavement construction, a tool that included the following attributes appears to be useful: (1) the ability to calculate energy/material consumption and constructing conditions without specialized knowledge of LCAs, (2) the ability to implement LCA in a standardized and reproducible manner and to scientifically quantify the environmental impacts that would be produced, (3) the presence of relevant and robust data for pavement LCA, (4) the presentation of visual LCA results (graphs) to help with interpretation.

This dissertation describes the development, testing, and assessment of such a tool, called Roadprint. This tool is an Excel-based pavement LCA tool, which allows pavement practitioners, including designers, engineers and owners, to incorporate LCA into their pavement projects. Roadprint streamlines the LCA processes by building a well-defined system boundary and robust data inventory for pavement practitioners. Users only have to enter general project information, such as pavement dimension, HMA tonnage, mix design, transporting distance for each material, and equipment use. This tool allows users to obtain quantitative results, such as energy consumption and greenhouse gases emissions, which can be used to assist in decision-making and provide anticipated reporting data.

1.4 Research scope

The scope of this research is listed as follow:

1) Define a suitable framework and system boundary for a LCA specifically for pavement construction. This research reviewed and evaluated different LCA approaches, current pavement LCAs and available pavement LCA tools. To arrive at a suitable framework and system boundary for pavement LCA. This is described in Chapter 2.
2) Obtain reliable LCI results. This research evaluated data sources and identified the most appropriate publically available data for use with pavement LCA. This is also described in Chapter 2.

3) Develop a software tool for pavement LCA, called Roadprint, to allow pavement professionals (designers, contractors, owners) to perform a pavement LCA without specialized LCA knowledge. This tool can perform both deterministic and probabilistic LCA. Alternative materials and advanced technologies for pavement construction were studied and applied in this LCA model. In this tool, U.S.-centric data and most up-to-date data sources are used for executing a pavement LCA. This is described in Chapter 3.
4) Test and compare Roadprint with other public available tools. This was done using six standard pavement designs and data from three actual pavement construction projects. This is described in Chapter 4.

Chapter 2. Life cycle assessment (LCA) and pavement LCAs

2.1 LCA overview

There are many tools that can aid the evaluation of environmental impacts, such as environmental impact assessment (EIA), risk assessment (RA), and substance flow analysis (SFA). However, LCA is the only tool able to evaluate the environmental impacts of a product or a function through the material's entire life using scientific and standardized methodology (as shown in Figure 4). LCAs use relatively objective information and can, thus, help ground environmental decisions on a solid footing.

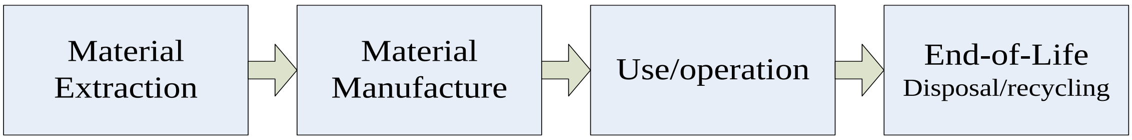


Figure 4 Life cycle of typical products

In LCA, all information of a product's life is taken into account: first, related environmental loads, such as energy, raw materials and wastes, of a specific product/function are quantified and used as input data; second, environmental impacts, such as emissions and leachate, are assessed and categorized as output data and interpretations; finally, decisions for this product or improving alternatives for specific processes are evaluated and identified (UNEP, 1996). In a typical LCA framework, these three stages are divided into eight steps, as shown in Figure 5.

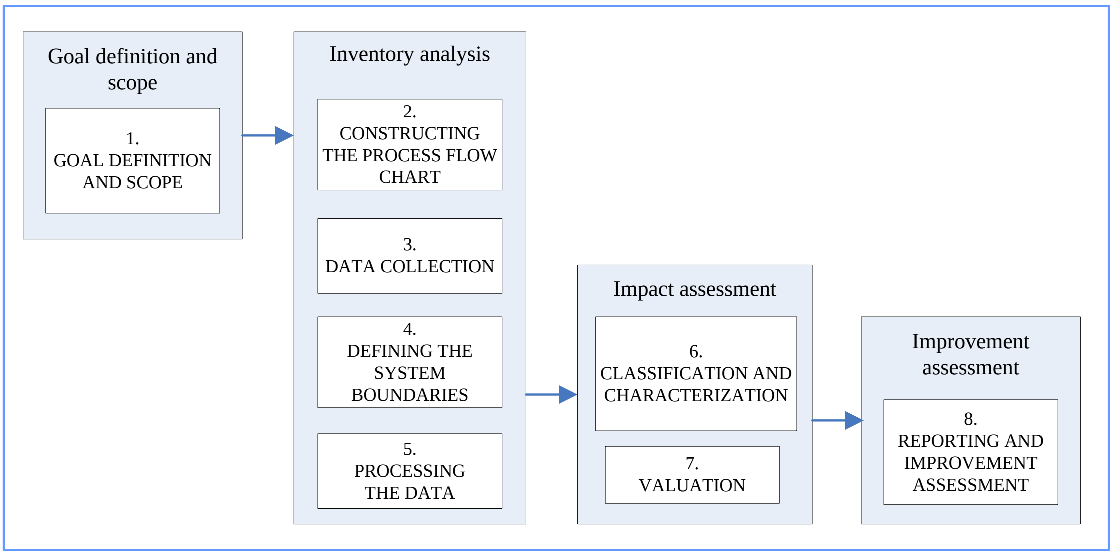


Figure 5 The framework for LCA (SETAC, 1994)

From 1997 through 2006, this framework was developed into a standard that is now contained in the International Organization for Standardization (ISO) 14000 series. Figure 6 shows an updated framework from ISO (ISO, 2006).

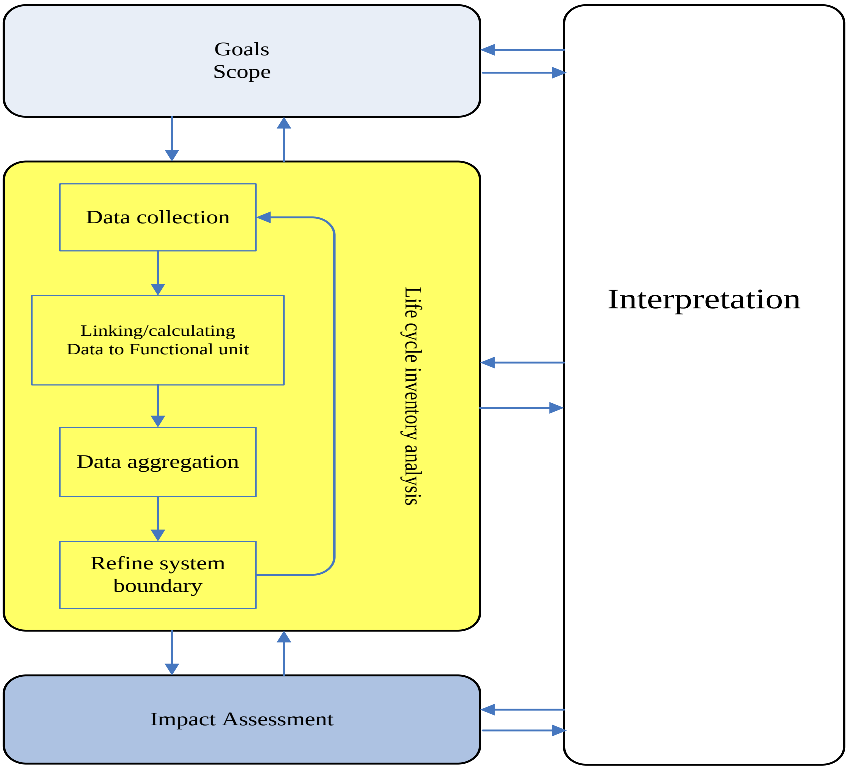


Figure 6 The framework for LCA (*Source*: ISO, 2006)

The ISO 14000 series essentially describes process-based LCA (PLCA), which is the original, or classical LCA approach (described in Section 2.2). There are five steps in the standardized LCA approach: (1) goals, (2) scope definition, (3) life cycle inventory analysis, (4) impact assessment, and (5) interpretation. Sections 2.1.1 to 2.1.5 give a brief description of this approach (Suh et al., 2004; ISO, 2006).

2.1.1 Goals

This step, states the intended goals for an LCA. Usually, the goals of an LCA are to address the environmental impacts of specific, well-described productions or activities. The goals step also outlines the reasons for conducting this study, the intended applications, and the intended audience. Setting goals helps to determine what method to use and where the boundary should be drawn.

2.1.2 Scope definition

This step defines the product's system or functional unit, the processes in the functional unit, and the system's boundary. In addition, assumptions and limitations are addressed.

A functional unit is usually defined and used to describe a quantity of an item produced or the duration of the item's activities. The functional unit can then be decomposed into a certain amount of unit processes, which represent the most fundamental and smallest economic activities involved in that process.

This step ensures that the product's system and functions can be compared appropriately (e.g., comparing a 1 Liter bottle of water to a 1 Liter carton of water). Processes included in a functional unit are the activities necessary for the functional unit and their corresponding environmental outputs in the LCA system.

An ideal LCA should include all processes that occur in the functional unit so that it can completely capture the reality. However, this can be difficult given constraints in time, cost, and data availability. Furthermore, some processes only make relatively minor contributions (e.g., striping in pavement construction) and might not significantly change the results of the analysis. Hence, an initial system boundary is set to remain focused addressing the goals established in step 1.

The system's boundary defines what unit processes are to be considered in the LCA and what unit processes are to be considered as inputs and outputs of the system. This boundary is also set to achieve the level of detail desired to meet the goals established in the first step. Usually, a system's boundary would need to be modified to help avoid a poor data quality score and conduct a more efficient LCA.

2.1.3 Life cycle inventory (LCI) analysis

This step quantifies inputs and outputs for given functional units. Tasks include data identification, collection, impact assessment (characterization), calculation, and validation. This step also serves as feedback to refine the goals, scope, and the system boundary. For instance, plastic bottles may replace cartons as a functional unit if there are no data for cartons available.

2.1.4 Life cycle impact assessment (LCIA)

This step assesses potential environmental impacts with the aid of the results from the inventory analysis. Tasks include the selection and the definition of impact categories and indicators, as well as the classification and characterization of impacts. Table 1 shows an example of terms in impact categorization.

Table 1 Example of Impact Categorization

Term	Example
Impact category	Climate change
LCI results	Amount of greenhouse gas per functional unit
Characterization factor	Global warming potential for each greenhouse gas (kg CO_2-equivalent/kg gas)
Category indicator results	Kg of CO_2 equivalents per functional unit

2.1.5 Interpretation

This step draws conclusions and makes recommendations based on the analysis. The examination of data quality and any significant issues during the LCIs and LCIA phases are also identified. Critical reviews by independent experts are used wherever possible.

2.1.6 LCA example

This section describes a simplified LCA example for pavement surface material in order to introduce the LCA process.

Step 1: Goal and scope

The goal of this LCA is to understand how much emissions will be produced and how much energy and resources will be consumed during the considered life cycle. In the definition of the scope, the functional unit is set as “a kilogram of hot mix asphalt (HMA).” Production and end-of-life are the life phases considered in the scope. In the system’s boundary, aggregate and bitumen are material inputs; electricity is the only energy input, but its production is not included. CO_2 is the only target emission. Therefore, in this LCA, the processes are (1) production of aggregate, (2) production of bitumen, (3) production of HMA, and (4) disposal of HMA. Figure 7 illustrates the LCA’s processes within the system boundary.

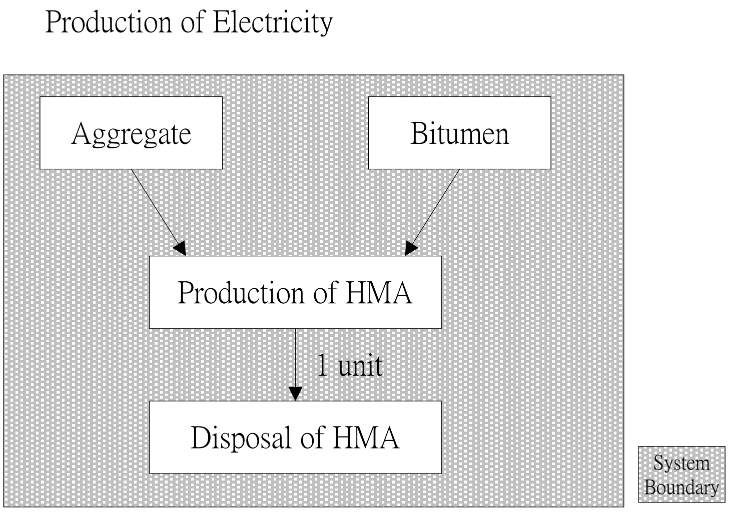


Figure 7 LCA process flow of HMA

Step 2: Lifecycle inventory analysis

The consumption and emission data are then collected and the inventory analysis is implemented as shown in Figure 8.

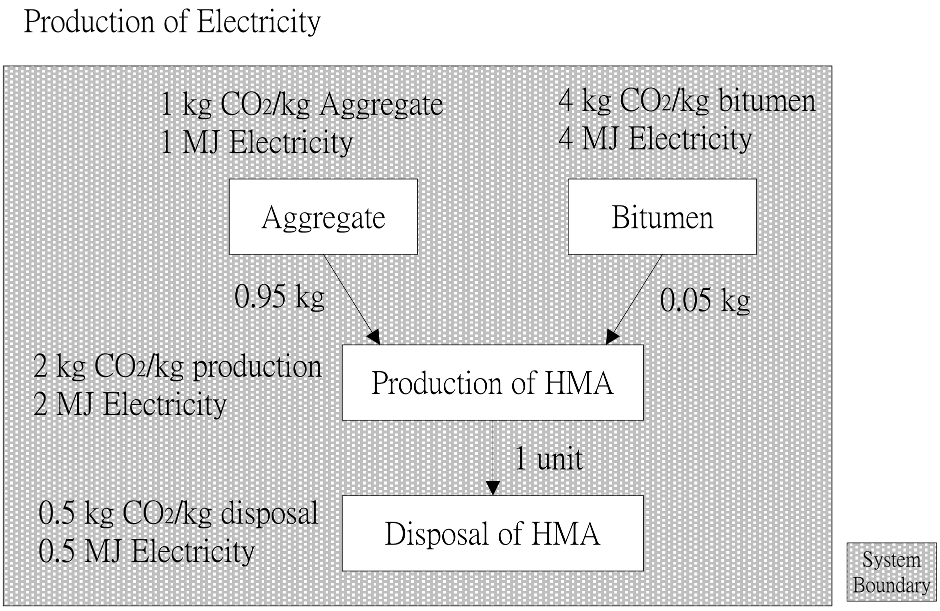


Figure 8 Data collection for processes of HMA

$$\left(\frac{1\ kgCO_2}{kg\ agg.}\cdot 0.95\ kg\ agg.\right)+\left(\frac{4\ kgCO_2}{kg\ bitumen}\cdot 0.05\ kg\ bitumen\right)$$
$$+\left(\frac{2\ kgCO_2}{kg\ HMA\ prod.}\cdot 1\ kg\ HMA\right)+\left(\frac{0.5\ kgCO_2}{kg\ HMA\ disposed}\cdot 1\ kg\ HMA\right)$$
$$= 3.65\ kg\ CO_2$$

$$\left(\frac{1\ MJ\ elec.}{kg\ agg.}\cdot 0.95\ kg\ agg.\right)+\left(\frac{4\ MJ\ elec.}{kg\ bitumen}\cdot 0.05\ kg\ bitumen\right)$$
$$+\left(\frac{2\ MJ\ elec.}{kg\ HMA\ prod.}\cdot 1\ kg\ HMA\right)+\left(\frac{0.5\ MJ\ elec.}{kg\ HMA\ disposed}\cdot 1\ kg\ HMA\right)$$
$$= 3.65\ MJ\ elec.$$

Step 3: Lifecycle impact assessment

Impact indicators also include LCA outputs, energy and CO_2. Therefore the result of the lifetime impact assessment is identical to the lifecycle inventory analysis (step 2) for this example.

Step 4: Interpretation

According to the results of the inventory analysis (step 2), each process can be further analyzed to identify critical processes in this LCA. For example, the energy consumption for bitumen production is 4 MJ/kg. If the energy efficiency improves from 4 MJ/kg to 3 MJ/kg, the total emissions will decrease from 3.65 kg to 3.15 kg:

$$\left(\frac{1\ MJ\ elec.}{kg\ agg.} \cdot 0.95\ kg\ agg.\right) + \left(\frac{3\ MJ\ elec.}{kg\ bitumen} \cdot 0.05\ kg\ bitumen\right) + \left(\frac{2\ MJ\ elec.}{kg\ HMA\ prod.} \cdot 1\ kg\ HMA\right) + \left(\frac{0.5\ MJ\ elec.}{kg\ HMA\ disposed} \cdot 1\ kg\ HMA\right) = 3.15\ MJ\ elec.$$

If the emissions of the disposal process decrease by 50%, then the total emissions will decrease from 3.65 kg to 3.4 kg:

$$\left(\frac{1\ kg\ CO_2}{kg\ agg.} \cdot 0.95\ kg\ agg.\right) + \left(\frac{4\ kg\ CO_2}{kg\ bitumen} \cdot 0.05\ kg\ bitumen\right) + \left(\frac{2\ kg\ CO_2}{kg\ HMA\ prod.} \cdot 1\ kg\ HMA\right) + \left(\frac{0.25\ kg\ CO_2}{kg\ HMA\ disposed} \cdot 1\ kg\ HMA\right) = 3.4\ kg\ CO_2$$

2.2 Current life cycle assessment practices

Several LCA derivatives have been proposed and implemented for various reasons. The PLCA was the first form to be developed and is typically viewed as the classical LCA ((Suh et al., 2004; SAIC, 2006)). The “streamlined LCA” seeks to provide a useful result while saving time and effort. The EIO-LCA uses industrial-average data instead of process-specific data, avoiding the most time- and cost-consuming procedures of LCA, i.e., data acquisition. The “hybrid LCA” combines the process-based and EIO-based data to avoid inherent flaws and to exploit the advantages from both methodologies. Section 2.2.1 to 2.2.5 provides the background, procedure, and pros and cons of each derivative.

2.2.1 Process-based LCA (PLCA)

Since formal LCA guidance and standards were published by the Society of Environmental Toxicology and Chemistry (SETAC) and the ISO in the early 1990s, PLCA has been considered the classical and mainstream LCA approach (Suh et al., 2004; SAIC, 2006). This LCA consists of a selected product system or functional unit defined to meet desired functional requirements. Typically, it can be broken down into separate processes. For example, a ton of HMA (a functional unit) can be separated into asphalt production, aggregate production, additive production, HMA plant operating, bitumen/aggregate/HMA transport, and energy generation. Each one of these processes can be further broken down into smaller processes. For example, HMA plant operating is composed of aggregate/bitumen heating, drum plant operating, fuel transportation, conveyer operating, loader operating and bitumen storage. Ultimately, one arrives at the most basic processes, the so-called unit processes, which cannot be further reduced (PLCA attempts to describe every single unit process within the system boundary) over the life cycle of the functional unit (ISO, 2006).

Theoretically, if all unit processes are described, a PLCA can produce a precise LCI for a very specific functional unit (e.g., a 1-lane mile of HMA pavement produced in a specific year, at a specific facility, and placed by specific equipment). Thus, in theory, PLCA is able to describe very detailed and specific outcomes.

However, a functional unit could be (and usually is) composed of a large number of processes, resulting in high demands in terms of time, cost, and manpower to collect the necessary data to describe them. The location of the system's boundary can also be controversial because it is not rigidly fixed by the procedure, and it determines which processes are included and excluded. Thus, different practitioners and stakeholders tend to draw different system boundaries, making it difficult to compare results. For example, energy usage and emissions by traffic are not included in all pavement LCAs.

2.2.2 Streamlined LCA

Streamlined LCAs were proposed by LCA practitioners in the mid-1990s (Todd and Curran, 1999). The purpose of such LCAs was to limit the number of described processes in an effort to overcome the major burden of the PLCA – data collection and missing processes.

A streamlined LCA conducts the LCA under the same framework as the PLCA but puts more effort into clarifying the needs and objectives of the LCA in advance. The goal and scope process is critical in streamlining practice; the system's boundary (data cut-off) is drawn by standardized streamlining options instead of through arbitrary decisions as in regular LCA. Those options include excluding (or partially excluding) up/downstream processes, limiting raw materials, using surrogate process data, etc. To determine which option will be used, all processes involved in a product are assessed and categorized into different levels of significance, which are usually defined by researchers, users, and sponsors. For processes that are more significant and might be evaluated by quality or quantity, detailed and quality data are required; for those that are less significant, processes might be excluded or replaced by similar processes (Curran and Young, 1996).

The advantage of a streamlined LCA is that it adds some structure in determining what processes to include/exclude. As a result, it can help save resources by only including processes that are deemed significant and relevant to the goal of the study. Ultimately, streamlined LCA is essentially PLCA with a uniform data cut-off mechanism. Therefore, hereafter these two methods will be discussed under “PLCA.” The disadvantages with streamlined LCAs include the following: all discharges are considered as having equal environmental impacts, which is generally not true; the results are more subjective because of the subjective nature of establishing the criteria to exclude processes; and there is unintentional omission of important impacts by using a standardized cut-off method.

2.2.3 Economic input-output LCA

Traditional PLCAs assess environmental burden based on a defined system boundary. Thus, their results are limited by (1) the somewhat arbitrary, or at least subjective, location of the boundary (and the inclusion and exclusion of processes), and (2) the often difficult task of gathering data on certain processes that may be nonexistent, incomplete, confidential or otherwise unavailable (Lave et al., 1995).

Economic Input-output (EIO) analysis was proposed by Wassily Leontief in the 1930s. This model divides the economy of a country into industry-level sectors that represent individual activity in the selected economy and depicts the economic interaction of industries (sectors) in a nation (or a region) by showing how the output of each sector is used as an input for others. The inherent system boundary is the country's economy. Those interactions depicted in the model are represented by monetary value in a matrix form, called the Input-Output table. The data stored in the table are collected by public agencies (e.g., the Department of Commerce) during a specific time period (usually 5 years). An I-O table could have 50 to 500 sectors, depending on how detail the entire economy is described. A sector could be composed of several industries or economic activities. When industries are categorized in the same sector, national average data for each industry are aggregated into the defined sector. The more sectors it contains, the more economic activities (identified industries) can be addressed by the data, consequently results in more precise description. The I-O table, combined with noneconomic data and unit conversion (the unit of the input-output model is monetary), is compatible with LCA methodology. Researchers at the Green Design Institute of Carnegie Mellon University proposed a modified LCA called the EIO-LCA in the mid-1990s. Compared to all the data needed for implementing a PLCA, EIO-LCA avoids the need to collect individual process data, consequently reduces the time and resource on data collection. Furthermore, as the data contained in the I-O table is public, EIO-LCA avoids proprietary issues. Accordingly, the EIO-LCA can produce economy-wide, system-level results, which avoid the insufficiencies of the process-specific approach (Hendrickson et al., 1998; 2006).

The issues for EIO-LCAs include the following: (Green Design Institute, EIO-LCA web page, 2009):

1) Data issues
    a. Environmental impact data for each EIO sector is often incomplete. Therefore, the model may underestimate the total environmental impacts.
    b. The use of sector-average data results in inconsistent data quality.
    c. Data collection for the I-O table is usually done every 5 years, so it could be antiquated, and the monetary values of that year or economic relationships between sectors often change over time.
    d. The use of sector-average data also results in aggregation. Several types of industries are represented only by a represented average, which leads to uncertainty.
2) International effects cannot be assessed because the system boundary is set as the whole economy of a particular region or country.
3) Different levels of aggregation could take place when applying EIO tables from different countries or databases. For example, there are 491 sectors in the U.S.'s table (1997), 117 sectors in Canada's table (1997), and 104 sectors in Japan's (2000) (Weber and Matthews, 2007).

4) The phases of use, operation, and end of life are not included in the I-O model, thereby limiting the precision.

2.2.4 Hybrid LCA

The hybrid LCA is an attempt to combine the advantages of process-based and I-O-based LCAs (Suh et al., 2004). More precisely, the approach complies with the standard LCA framework but employs both types of data. This approach was developed in the 1970s, but was not performed until the late 1990s.

The hybrid LCA can be further categorized into the following types: tiered hybrid analysis, I-O-based hybrid analysis, integrated hybrid analysis, and process-based hybrid analysis (Suh et al., 2004). The data types, the boundaries between the I-O and process-based data, and the flow of each hybrid model are shown in Figure 9. The figure aids understanding of the basic ideas of each hybrid LCA. In Figure 9, (a), (b) and (c) represent tiered, IO-based, and process-based hybrid models, respectively.

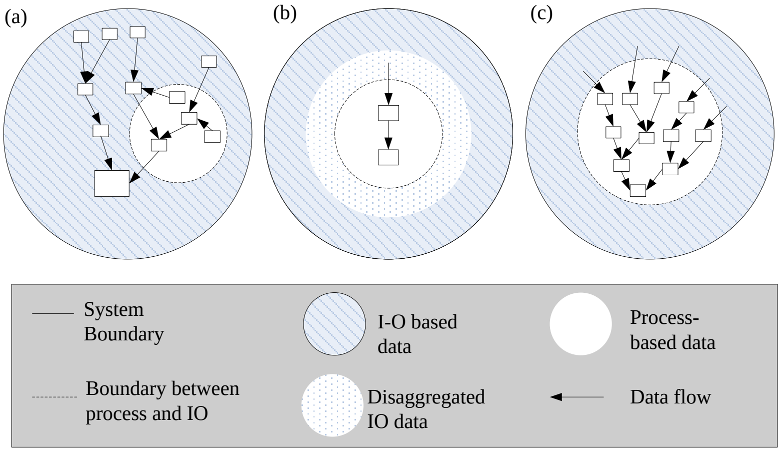


Figure 9 Data flows and boundaries in different hybrid LCAs (a) tiered hybrid (b), I-O-based hybrid, (c) process based hybrid (Suh and Huppes, 2005)

Tiered hybrid LCA: The first tiered hybrid LCA was proposed by Bullard et al. (1978). As shown in Figure 9(a), a functional unit can be added as a hypothetical economic sector in an I-O model. There is no environmental information for this sector. Then, the functional unit will be disaggregated and categorized into typical and atypical subsystems; typical ones are addressed by I-O analysis, whereas atypical ones are addressed using process-based analysis, or are further disaggregated. The iterative disaggregation procedure enables the tiered hybrid LCA to utilize the easily accessible I-O model to obtain information for typical subsystems, while selected processes use available process-based data, consequently obtaining more detailed results (Bullard et al., 1978).

As it uses the I-O-based approach (at least partially), the tiered hybrid method can save resources on data collection and inventory results. The disadvantages include: (1)

double counting: atypical subsystems are chosen to be represented by process-based flows, but some are already contained in existing I-O sectors (e.g., the process "paper production" can also be found in the sector "paperboard containers and boxes"); and (2) a decrease in specificity: some significant processes would be better assessed by process-based analysis rather than by the I-O-based method (Bilec et al., 2006; Joshi, 2000).

I-O-based hybrid LCA: Most products are contained in existing I-O sectors; therefore, the I-O-based hybrid LCA proposes disaggregating I-O sectors that contain the product of interest and supplementing process-based information of certain phases for the products. For example, "paper cups" is contained in the sector "paperboard containers and boxes." This sector can be disaggregated into "all products in paperboard containers and boxes except paper cups" and "paper cups." The sector "paper cups" is then disaggregated into "glue production," "wax production," and others. By iteratively introducing new sectors, the existing I-O table becomes more specific (Treloar, 1997; Joshi, 2000). Process-based data are only used for "use" and "end-of-life" phases to compensate for the life phases omissions in the I-O analysis. This procedure is shown in Figure 9(b).

The I-O-based hybrid LCA can avoid the problem of double counting because no process-based data are used except in the last two life phases. The major downsides are that the I-O table lacks the use and end-of-life phases, so that information must be added using the tiered hybrid method; it is also unable to deal with imported goods because I-O tables are usually based on the economy of an individual country (Suh et al., 2004).

Process-based hybrid LCAs: Process-based hybrid analyses begin with process-based data for critical materials, energy usage, and environmental discharges. The life cycle is divided into several phases, and once the data collection reaches the system boundary (selected indirect flows), the best-matching I-O sectors are identified and modeled for those beyond the system's boundary (Guggemos, 2003; Guggemos and Horvath, 2005). Figure 9(c) gives an idea of how the data are used and what types of data are used in this method.

The major advantage of the process-based hybrid method is greater precision in LCI results; the major drawbacks are double counting and high demands for data and time.

2.2.5 Discussion

2.2.5.1 Comparison of process-based and I-O-based LCAs

The principal advantage of the process-based method is that it can evaluate and compare specific products (not just generic products) because it collects information on the actual processes related to that specific product (Sharrard, 2007). For instance, for a typical HMA pavement, the process-based approach can analyze a specific roadway section, which was constructed by a specific HMA plant, constructed by specific equipment, fueled by a specific fuel mix, and supplied with electricity with a specific power-generating mixture. However, this specificity also creates key disadvantages associated with the process-based approach.

First, it is not possible to describe every associated and constituent process, and a boundary must, thus, be drawn, outside of which other processes are not considered. For instance, a purely theoretical process-based approach would gather data not only on the machines that built a particular section of road, but also on the machine that built those machines in the equipment manufacturing plant, and the machines that built those machines, and so on. This approach is essentially circular and never-ending. Drawing a boundary solves this problem, but the placement of the boundary is subjective. It is certainly possible to estimate a point of diminishing return where additional processes do not add significantly to the LCI, but that particular point is still subjective. Furthermore, the required data for this approach can be missing, incomplete, or otherwise unavailable. Finally, collecting data is time and cost intensive.

The I-O based LCA data is publicly available, so costs and time can be saved, and the results are reproducible among practitioners. It does take the economy of an entire region or country into account; therefore, its system's boundary is consistent and comprehensive. Other drawbacks include data quality concerns from aggregating sectors, double counting issues, omission of use and end-of-life phase, which leads to underestimated system impacts, and inability to identify improvements at the process level.

The respective strengths and weaknesses of process-based and IO-based LCAs are compared and summarized in Table 2. In general, the two methods appear to have opposing constitutional strengths and weaknesses; the process-based method is superior on specificity but limited by truncation error; the IO-based method raises no concerns in relation to data collection, but tends to lack detail. Therefore, PLCA can be used when specific objects have to be assessed, whereas EIO-LCA offers opportunities for strategic policy decisions (comparing between sectors), as well as providing complementary data on sectors not covered by PLCA.

Table 2 Comparison of Process-based and I-O-based LCA (Sharrard, 2007)

Topic	***Issue***	***Process-based LCA***	***I-O based LCA***
Boundary	Analysis limit	Subjective	Entire economy
	Imports and exports	Feasible if data are available	Must be considered as products within the economic region
Data	Type	Public, private, proprietary	Public
	Age	Can be up-to-date	5+ years old at best
	Comprehensive	Subject to availability	Good
	Specificity	Good	All commodities included, although highly aggregated in some sectors
	Cutting-edge products	Feasible if data are available	No
	Units	Mostly physical	Monetary
	Uncertainty	Yes	Yes
Life cycle phase	Use/operation	Feasible if data available	No
	End-of-life	Feasible if data are available	No
Results	Type	Maybe LCIA	LCI
	Reproducible	If using public data	Yes
	Product/process comparisons	Feasible if data are available	No
	Process improvements	Feasible if data are available	Only at the sector level
Investment	Time	High	Low
	Cost	High	Low

2.2.5.2 Comparison of different hybrid LCA method

Hybrid LCA offers an opportunity to combine advantages from both process-based and I-O-based methods. They are classified according to the relative use of the process system and the I-O-based system within each model: tiered hybrid, I-O-based hybrid, and process-based hybrid. Similar to the arguments for process-based LCA and I-O-based LCAs, each method has its advantages and disadvantages, and it is difficult to select one of these hybrid LCAs approaches as universally superior to the others. The most appropriate model must be determined by considering the goal, scope, and resource constraints, such as time, budget, and data availability. Their respective strengths and weaknesses have been discussed in section 2.2.4 and are summarized in Table 3.

Table 3 Comparison Between Hybrid Approaches (*Source:* Suh et al., 2004)

Approach	**Strengths**	**Weaknesses**
Tiered hybrid	Easy to use	Double counting
I-O-based hybrid	Availability of literature, databases, and well-documented case studies Avoids double counting The process part and the I-O part are described in a consistent framework	Use and end-of-life phase are externally added to the main system Needs to be combined with other methods if the national economy is highly dependent upon imports
Integrated hybrid	Consistent mathematical framework for the whole life cycle Avoids double counting Easy to apply analytical tools	Relatively complex to use Data and time intensive

2.3 Introduction to pavement LCAs and tools

To date, various LCA methods and scopes had been applied in pavement LCA implementation (see Table 4 for examples). Systems’ boundaries and output interpretations are always slightly different according to each study's individual goals and scope. The specific system boundary in each pavement LCA is based on the desired life span, the selected life phase, the selected resource consumption, and the desired environmental burdens. Therefore, it is important to understand the different elements among different LCA studies. A checklist was developed to help pavement LCA practitioners prepare essential information before implementation, and also help reviewers to identify differences of LCAs among different studies (UCPRC, 2009).

This research reviews 17 papers (66 total assessments) in order to describe the state-of-the-practice for pavement LCA. Both HMA and Portland cement concrete (PCC), in terms of pavement structures, aggregate substitutes, base material substitutes, and various maintaining techniques are classified and evaluated by LCA approaches, goal/scope definition, the system's boundaries, and data collection. Also the types, tools, and locations of the selected assessments are summarized. The pavement's dimensions, life span, and life phases covered are also assessed.

Table 4 Pavement LCAs and Their Individual Features

	Type	Tool	References	Country	Pavement's features	Dimension		Service duration	Pavement's life cycle phases						
						Width (ft)	Length (mile)		MP	Const	Trans	MA	OP	U	EOL
1	EIO-LCA	N/A	Horvath and Hendrickson (1998)	U.S.	HMA	24.00	0.62	10 +	X	X	X				X
2					CRCP										
3	I-O-based hybrid	Pa-LATE	Horvath (2003)	U.S.	RAP	24.00	1.00	N/A	X	X	X	X			
4			Carpenter et al. (2007)	U.S.	HMA-natural	34.12	0.19	N/A	X	X	X	X			
5					HMA-BA										
6			Uzarowski et al. (2008)	Canada	Conventional HMA	37.48	4.66	50	X	X	X	X			
7					Perpetual										
8			Alkins et al. (2008)	Canada	HMA	24.61	0.62	50	X	X	X	X			
9					CIR										
10					CIREAM										
11			Nathman et al. (2009)	U.S.	Asphalt emulsion	12.00	1.00	N/A	X	X	X	X			
12					Ultrathin HMA										
13					RAP										
14					RAP with crumbed										

	Type	Tool	References	Country	Pavement's features	Dimension		Service duration	Pavement's life cycle phases						
						Width (ft)	Length (mile)		MP	Const	Trans	MA	OP	U	EOL
					rubber										
15					CIR										
16	Tiered hybrid	N/A	Treloar et al. (2004)	Australia	CRC	12.00	3.11	40	X	X	X	X		X	
17					PC			40							
18					FDA			40							
19					Comp			40							
20					DAS			40							
21					G			20							
22					DSAB			40							
23					ACB			20							
24	PLCA	N/A	Athena Institute (2006)	Canada	Art-PC-CBR3	26.25	0.62	50	X	X	X	X			
25					Art-AC-CBR3	24.61	0.62								
26					Art-PC-CBR8	26.25	0.62								
27					Art-AC-CBR8	24.61	0.62								
28					HV-PC-CBR3	26.25	0.62								
29					HV-AC-CBR3	24.61	0.62								
30					HV-PC-CBR8	26.25	0.62								
31					HV-AC-CBR8	24.61	0.62								
32					Quebec- PC	24.28	0.62								
33					Quebec-AC	24.28	0.62								
34					Ontario-PC	37.73	0.62								

	Type	Tool	References	Country	Pavement’s features	Dimension		Service duration	Pavement’s life cycle phases						
						Width (ft)	Length (mile)		MP	Const	Trans	MA	OP	U	EOL
35					Ontario-AC	36.09	0.62								
36		N/A	Stripple (2001)	Sweden	HMA-Hot	42.65	0.62	40	X	X	X	X	X	X	
37					HMA-Cold										
38					PC										
39		N/A	Häkkinen and Mäkelä (1996)	Finland	PC-main A	27.89	0.62	50	X	X		X	X	X	
40					PC-main B										
41					AC-main A										
42					AC-main B										
43		Excel-based model	Mroueh et al. (2000)	Finland	FA1	24.61	0.62	50	X	X	X	X		X	
44					FA2										
45					FA3										
46					CC1										
47					CC2										
48					BFS										
49					R1										
50		Excel-based model	Huang et al. (2009a)	U.K.	HMA-virgin	13.12	4.66	N/A	X	X	X				X
51					Glass, RAP, IBA in HMA										
52					RAP, IBA in HMA										
53					Glass, RAP in HMA										
54					Glass, IBA in HMA										

	Type	Tool	References	Country	Pavement's features	Dimension		Service duration	Pavement's life cycle phases						
						Width (ft)	Length (mile)		MP	Const	Trans	MA	OP	U	EOL
55			Huang et al (2009b)		HMA	22.97	1.61		X	X	X				
56		Eco-indicator 99	Chui et al. (2007)	Taiwan	HMA	8.69	0.62	40	X	X	X	X			
57					RAP										
58					AR-HMA										
59					Glassphalt										
60		N/A	Zapata and Gamtabese (2005)	U.S.	CRCP	23.62	0.62	N/A	X	X	X	X			
61					HMA										
62		N/A	Weiland (2008)	U.S.	PCC	12.00	1.00	50	X	X	X	X			
63					HMA										
64					CSOL										
65		ROADRES	Birgisdóttir (2005)	Denmark	HMA-natural	22.97	0.62	100	X	X	X	X	X		X
66					HMA-MSWI										

MP: material production Const: Construction Trans: Transportation MA: maintenance OP: operation U:Use EOL: end of life

PC/PCC: Portland cement concrete pavement; AC/HMA: asphalt concrete pavement; ART: arterial HV: high volume; AC-Hot: hot mixed AC; AC-Cold: cold mixed (emulsified) asphalt; main A/B maintenance plan A/B; FA: fly ash; CC1: crushed stone; BFS: burst furnace slag; R1: natural aggregate only; HMA: hot mix asphalt; RAP: recycled (reclaimed) asphalt pavement; IBA: incinerator bottom ash; glassphalt: HMA with glass as fine aggregate; CRCP: continuous reinforced concrete pavement; CRCP/CRC: continuous reinforced concrete pavement; BA: bottom ash; CIR: cold in-place recycling; CIREAM: cold in-place recycling expanded asphalt mix; FDA: full depth asphalt; Comp: composite, asphalt and concrete; DSA: deep strength asphalt; G: granular; DSAB: deep strength asphalt on bounded sub-based; ACB: asphaltic concrete on bounded sub-based; MSWI: municipal solid waste incineration

2.3.1 Goal and scope

The selected papers aimed to evaluate the impacts of pavements in terms of resource consumption and environmental burden through certain life cycle phases or spans. The most commonly applied design life of the pavements was 40 to 50 years, and the most common format of the functional unit was "number of lanes/length," such as a "2-lane/km" or a"1-lane/mile." The structures and thicknesses of the layers varied in each assessment. The dimensional parameters were based on the designed traffic load, equivalent single-axle loads (ESALs), and the analyzed service life.

All activities or unit processes that take place during the life span can be categorized into different life cycle phases. In terms of life cycle phases, common phases included materials production (MP), construction (const.), transportation (trans.), maintenance (MA), operation (OP), use (U), and end of life (EOL). "MP" includes steps from raw material extraction to manufacture of pavement materials. "Const" includes activities necessary for earthworks and placing pavement materials. "MA" in pavement LCAs usually includes regular maintenance and preservation. "OP" addresses operating activities, mainly lighting and signaling, during the "U" phase, which solely considers traffic (fuel consumption) during the life span. "EOL" means landfill disposal or recycling processes. As shown in Table 4, "MP," "const," "trans," and "MA" were mostly covered. A few PLCAs covered "OP" and "U" phases, whereas EIO-LCAs did not due to their inherent methodological constraints. Only three papers mentioned environmental impacts through the “EOL” phase.

In terms of environmental burdens, general scopes included raw materials, energy consumption, and airborne emissions. Water- and soil-borne emissions (including leachate) was a major topic in the studies of Mroueh et al. (2000) and Birgisdóttir (2005), whereas Horvath and Hendrickson (1998), Stipple (2001), Häkkinen and Mäkelä(1996), and Huang et al. (2009a) addressed this issue alongside air emissions. Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE), an I-O-based hybrid tool, is capable of addressing leaching, but only Horvath (2003), Carpenter et al. (2007), and Nathman et al. (2009) utilized it to reveal leaching results. Noise was taken into account only in the studies of Hakkenen et al. (1996), Mroueh et al. (2000), and Huang et al. (2009a).

2.3.2 System boundaries

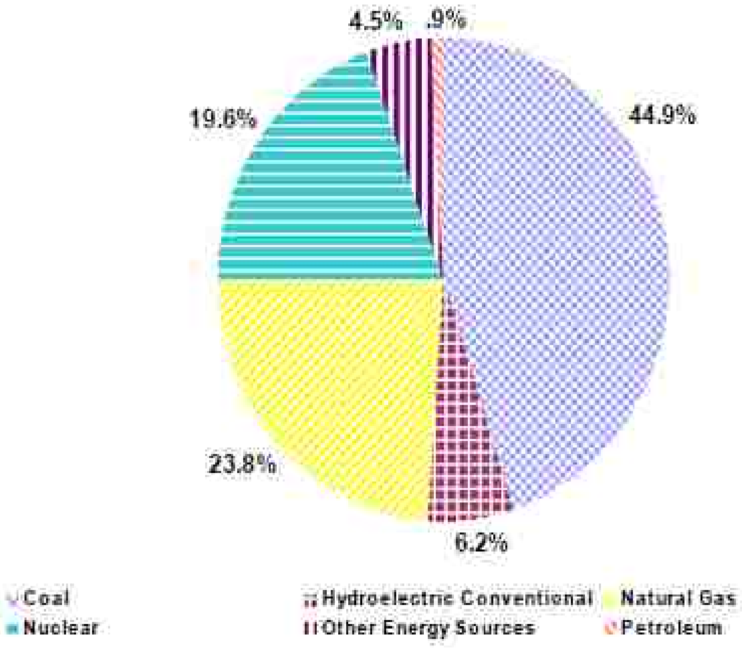
The goals, scope, and data availability varied in the papers; accordingly, the system’s boundaries were different. In this section, processes that were included and their components are listed and discussed to yield a better understanding of the general characters and individual issues relating to existing pavement LCAs.

2.3.2.1 Energy production

The most common types of energy consumed during all life phases included electricity, crude oil, fossil fuel, coal, natural gas, and wind/hydraulic power. These energy types can be integrated into Giga joules (GJ) as a general unit.

The production of electricity might utilize various energy sources, and the usage/composition might vary in different geographic locations. As shown in Figure 10, in Washington State, hydro-power provided 65% of the electricity generated, while it accounted for 8.2% of electricity production on average nationally in 2010USEIA, 2011; WSDOC, 2011).

(a)



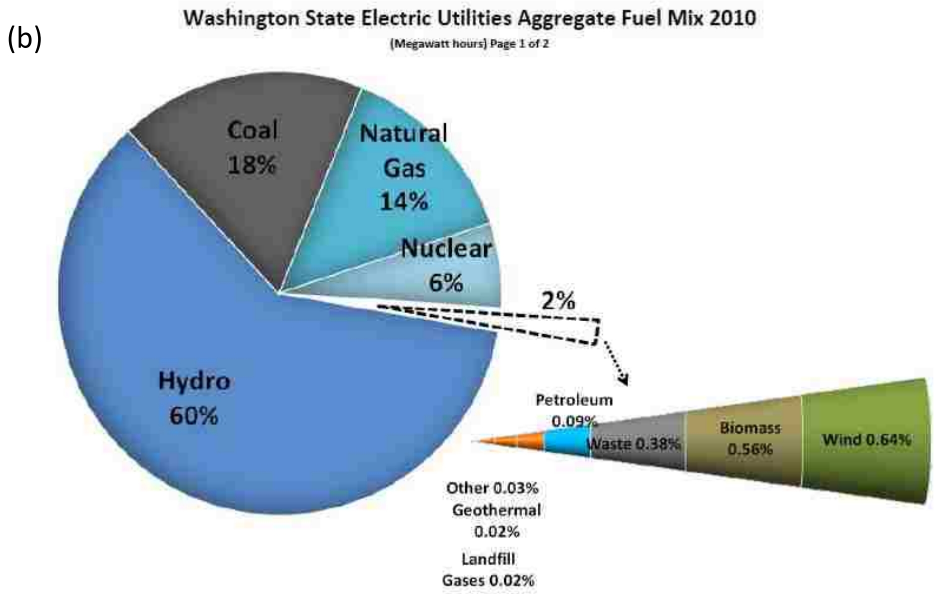


Figure 10 Electric utility use in 2010 (a) U.S. Electricity Mix in 2010 (b) Washington State (U.S. EIA, 2011; WSDOC, 2011)

The manufacturing of facilities to generate energy was not included in any pavement LCAs. For example, fuel is refined from crude oil (natural resource) at a refining plant, but the energy inputs/outputs involved in the manufacturing of the actual refining plant were never included in the system's boundary and were not considered in any existing pavement LCAs.

2.3.2.2 Production of material

In this phase, the unit processes used to produce the materials are first listed; natural resources and the energy used for each unit process (operating manufactured machines) were then identified. The manufacturing of these machines has not been covered in any other study.

Aggregate: Crushed aggregate, gravel, and sand were commonly included in the studies. The production processes of these materials usually include crushers, wheel loaders, conveyors, excavators, and blasting material. However, the production of blasting material was excluded from some studies (Stripple, 2001; Weiland, 2008). Zapata and Gambatese (2005) incorporated quarry-to-manufacture transportation into gravel extraction processes.

Asphalt: Bitumen, bitumen emulsion, and tack coating materials are all derived from crude oil refinery processes. The production of bitumen sometimes included the production of crude oil, as well as sea freight and refining (Stripple, 2001; Häkkinen and Mäkelä, 1996). Weiland (2008) used data from a report, "Eco-profile for paving grade bitumen," which specified the system's boundary, the unit processes, and even the grade of bitumen (Eurobitume, 1999).

Cement: Cement production includes raw cement material extraction, truck transportation, and clinker burning (Zapata and Gambatese, 2005). Weiland (2008) and Athena (2008) set system boundaries only at the point of PCC production and did not look at cement production. Details of cement production can be found in the papers of Marceau et al. (2007) and Stripple (2001)

Steel: dowel/tie bar and reinforced steel are common steel products used in PCC, reinforced concrete pavement (RCP), and continuously reinforced concrete pavement (CRCP). Hot dip galvanized steel is used for peripheral equipment (e.g., signs), and information on zinc production was used in Stripple (2001).

Aggregate/cement substitute: Blast furnace slag (BFS), crushed concrete waste, fly ash (FA), rubber, bottom ash, and recycled glass were considered as replacements for aggregate or cement. The manufacture of these materials is often excluded in pavement LCAs because they are mostly by-products or the waste of other processes. Therefore, only transport processes were included (Huang et al., 2009a). If the manufacturing processes are taken into account, the environmental benefits of using these wastes or by-products might be significantly less, or even eliminated, e.g., asphalt rubber HMA (Chui et al., 2008) or crushed cement concrete (Horvath, 2004). However, the current manufacturing processes of these by-products need to be more specifically described as an individual product, to deliver more significant LCA results.

HMA: The production of HMA usually included material conveyance within the plants, aggregate drying, bitumen heating, and mixing of the material. The energy usage and environmental burden depend on the type of mixing plant and the source of energy.

Cold-mixed asphalt (CMA): CMA was only discussed in the work of Stripple (2001), noted that bitumen is emulsified into an emulsion and mixed at a lower temperature, which results in less energy requirements, as well as emissions.

PCC: As noted by Athena (2008) and Weiland (2008), PCC production processes could include aggregate production, cement production, additive production, transportation, and mixing of materials. The energy usage and environmental burdens of the mixing process depend on the mixing type and capacity of the mixing plant.

Reclaimed asphalt pavement (RAP): RAP can serve as a source of both bitumen and fine aggregate, consequently reducing energy requirements and environmental impacts. The production of RAP can include manufacture (milling), collecting, and transportation. Athena (2006) specified that the inherent energy in RAP was excluded in its study, whereas no other paper mentioned the inherent energy in RAP.

2.3.2.3 Construction

In this phase, the units of the construction activities were listed. The energy used (mostly fuel and electricity) in each unit process (operating construction equipment) was then identified. The manufacture of construction equipment was not included in any of the studies.

Demolition: The demolition equipment discussed included breakers, drop hammer trucks, excavators, loaders, and trucks. Stripple (2001) provided energy consumption and emissions information for those specific equipment. In another study, data of equipment was estimated by using diesel engines similar to those were used, except for trucks (Weiland, 2008). Athena (2008) excluded this process due to a lack of data.

Paving: Processes associated with operating asphalt pavers and PCC placers/spreaders were covered. Stripple (2001), Häkkinen and Mäkelä (1996), and Zapata and Gambatese (2005) assessed these processes using survey data, whereas Weiland (2008) estimated them using similar diesel engines. Only Weiland (2008) included a material transfer vehicle (MTV) in the paving process, even though MTVs are often used and sometimes required by specifications in the construction of pavements.

Rolling: The base course and sub-base course need to be compacted before laying surface materials. After the placement of HMA, breakdown rolling and finish rolling are carried out to achieve the desired density of the pavement. These processes, including rubber tire rollers and steel wheel rollers, were covered in all the assessments.

Grading: This process was addressed independently by Weiland (2008); Athena (2006) incorporated this process into base preparation.

Joint sealing: Stipple (2001) and Häkkinen and Mäkelä (1996) specified the processes of joint sealant production and its application. Häkkinen and Mäkelä (1996) further specified the exclusion of inherent energy in sealing materials. Weiland (2008) only addressed the application process. Athena (2006) incorporated this process into maintenance.

Texturing: Only Zapata and Gambatese (2005), Athena (2006), and Weiland (2008) took this process into account, even though it is almost always part of PCC paving.

Saw-cutting: Saw-cutting is necessary for all PCC pavements to avoid shrinkage cracking. Weiland (2008) specified this process separately, whereas Stripple (2001) and Athena (2006) incorporated this process into other construction processes.

Traffic delays: Huang et al. (2009 b) included emissions from traffic delays at work zones. The results showed that shortening construction by three days could save as much as 4.50E+04 g of CO and 9.00E+04 g of PM emissions. No other emissions were significant and no other studies considered traffic delays as part of LCA.

2.3.2.4 Transportation

In this phase, the unit processes of transportation activities were listed. The energy used (mostly diesel) for each unit process (operating transportation equipment) were then identified. The manufacture of this equipment was not included in any of the studies.

Trucking: Truck haulage was the most common way of delivering the material. This process was addressed by energy usage and environmental burden per unit distance. The hauling distances of all the materials were either assumed or measured.

Sea freight: Sea freight was often used for delivery of crude oil and salt (Stripple, 2001; Athena, 2006). This process was addressed by energy usage and environmental burdens per unit distance.

Rail transport: Rail systems have higher fuel efficiency than trucks. Only Huang (2009a; 2009b) addressed this process.

2.3.2.5 Maintenance

In the pavement industry, the terms “maintenance” and “preservation” represent different activities. However, “maintenance” in pavement LCAs usually includes both regular maintenance and preservation. In this study, “maintenance” is used to cover both ideas. Fourteen papers were analyzed in this phase. The types of maintaining techniques were listed. The energy used (mostly diesel and electricity) for each unit process (operating the maintenance equipment) was then identified. The manufacturing of the maintenance equipment was not included in any of the studies.

Treloar (2004) did not specify the maintenance processes and only assumed an annual cost of 4% of initial construction.

Patching: This process was mentioned but excluded from the system's boundary in Athena's assessment (2006). Stripple (2001) incorporated the patching process into an integrated miscellaneous construction process. Only Weiland (2008) addressed this process by operating equipment with similar engine size.

Milling: Milling can serve as a maintenance process, as well as a production process for RAP. Stripple (2001) and Weiland (2008) segregated milling processes, whereas Häkkinen and Mäkelä (1996), Birgisdóttir (2005) and Athena (2006) incorporated it into maintenance processes.

Diamond grinding: Diamond grinding can rehabilitate a rough PCC pavement to a smooth surface. Weiland (2008) specified this process, and Athena (2006) incorporated it into PCC rehabilitation.

Cold in-place recycling (CIR): Processes in CIR include milling, mixing with emulsifier/virgin aggregates, and relaying. Alkins (2008) and Nathman et al. (2009) addressed the CIR process.

Crack, seat, and overlay (CSOL): Processes for CSOL include PCC cracking, seating of cracked PCC, sweeping, tack coating, and HMA paving. Only Weiland (2008) addressed this maintenance technique.

Dowel bar retrofit (DBR): Processes for DBR include dowel bar production, dowel slot cutting, slot cleaning, waste transport, slot patching, and diamond grinding. Only Weiland (2008) addressed this maintenance technique.

2.3.2.6 Operation

Only three papers analyzed this phase (Stripple, 2001; Häkkinen and Mäkelä, 1996; Birgisdóttir, 2005). The unit processes of the operating activities were listed. The material usage (salt) and energy usage (mostly electricity and diesel) for each unit process (operating transporting equipment) were then identified. The manufacturing of the operating equipment was not included in any of the studies.

Lighting: Lighting includes traffic control and general lighting. Stripple (2001) assumed no differences between lighting on PCC and HMA pavements. Häkkinen and Mäkelä (1996) specified the different lighting requirements on PCC and HMA pavements which were 150 watts for PCC and 250 watts for HMA.

Salting: Stripple (2001) considered processes of salt production, transport, and spreading. Häkkinen and Mäkelä (1996) specified the environmental burden of salting, but did not consider different salting requirements between PCC and HMA pavements. Birgisdóttir (2005) considered snow salting during winter but did not specify the process.

Cleaning: Weiland (2008) addressed the sweeping process by using information available for similar types of engines, although it was designated for sweeping a surface after milling only. Stripple (2001) addressed the cleaning and washing processes.

2.3.2.7 Use

Four papers took the “use” phase into account in their assessment :(1) Treloar et al. (2004), (2) Stripple (2001), (3) Häkkinen and Mäkelä (1996), and (4) Mroueh et al (2000). Generally, the “use” of the pavement refers to the vehicles operating on the roads, which can also be viewed as a unit process. The energy used (mostly fuel) and the emissions of each unit process were then identified.

Traffic composition: The volume of traffic was also estimated in the four papers mentioned in the last section. Stripple (2001), Häkkinen and Mäkelä (1996) did not consider different types of vehicles, whereas Treloar et al. (2004) and Mroueh et al. (2000) classified the traffic into automobiles and trucks.

Vehicle/truck manufacturers: This factor was only considered by Treloar et al. (2004). More specifically, he examined an energy-only perspective, and examined the energy use of the manufacture, maintenance, and replacement processes of vehicles and trucks. The results showed the energy used by vehicle/truck manufacture could be two times more than the energy use in initial construction, but the calculation was based on several assumptions: vehicle price, vehicle life, daily volume and daily travel distance.

2.3.2.8 End of life

The “end of life” phase was examined in three papers: Horvath and Hendrickson (1998), Birgisdóttir (2005), and Huang et al. (2009a). The two common treatments in this phase are recycling and landfill. All three papers discussed recycled materials and their impact, but none described substantial recycling processes. Huang et al. (2009a) listed depletion of landfill space as one of its impact categories, but no other information was revealed. On the other hand, Birgisdóttir (2005) considered the environmental impacts of municipal solid waste incineration in landfills but not the impact of waste pavement materials in landfills.

2.3.3 Impact categories and environmental burdens

Impact assessments are used to reflect the corresponding goals of LCAs. General impact categories will be discussed in section 2.3.3.1. The environmental burden can be divided into natural resources consumption and emissions to air or water. The scope of natural resources (energy and raw materials) has already been discussed in 2.3.2.1 and

2.3.2.2. Thus, in this section outputs from pavement construction to the environment that have been specified in literature are listed.

2.3.3.1 Impact categories

Four papers included information on environmental impact categories, and all differed slightly according to the individual goals and the system's boundaries (Horvath, 2003; Birgisdóttir, 2005; Huang, 2009a; Weiland, 2008). For example, Birgisdóttir (2005) was the only one to use stored eco-toxicity, perhaps because long-term effects of landfill were included in the research scope. Commonly used categories are listed below:

1) Global warming: climate change due to increasing levels of greenhouse gases
2) Acidification: acidification of the air, soil, or aquatic system as a result of an increase in the release of hydrogen ions, thus, reducing the neutralizing capacity of natural acids
3) Human toxicity from the air/water/soil: compounds that are toxic to humans
4) Eutrophication: increased concentrations of N and P nutrients in aquatic systems, consequently leading to degradation of water quality
5) Stratospheric ozone depletion due to emissions of volatile chlorine halocarbon and bromine halocarbon

6) Eco-toxicity from compounds that are toxic to eco-systems
7) Stored eco-toxicity resulting from compounds that have the potential to cause eco-toxicity in an infinite time horizon
8) Photochemical smog resulting from photochemical oxidation of volatile organic compounds (VOCs), carbon oxide, sulfur dioxide, and nitrogen oxides.

2.3.3.2 Air emissions

Although all 17 papers took air emissions into account, not all of the papers specified what emissions they measured and assessed. Uzarowski et al. (2008, two assessments) used PaLATE, which can assess air emissions, as their LCA tool, but they did not reveal the related results; Treloar et al. (2004, eight assessments) and Zapata and Gambatese (2005, two assessments) focused on energy consumption but did not include air emission results; Chui et al. (2008, four assessments) converted environmental impacts into personal equivalents (ecological footprint of 100 Europeans) and, thus, provided no direct emissions information. Consequently, 50 assessments reported the environmental burden of airborne emissions. 18 types of emissions were reported: CO_2, CO, NO_X, NO_2, SO_X, SO_2, VOC, CH_4, HC, $PM_{2.5}$, PM_{10}, N_2O, HCl, benzene, COD, H_2S, and NH_3. These emissions data sets were measured and collected to evaluate environmental impacts according to the impact categories mentioned above. Due to a lack of data availability, not all emissions were taken into account in every single assessment. Table 5 lists the most common emissions, defined as reported more than 20 times in pavement LCAs.

Table 5 General Airborne Emissions in Pavement LCAs

Airborne emissions tally (50 in total)							
CO_2	NOx	CO	SO_2	PM_{10}	CH_4	N_2O	VOC
48	36	31	33	28	27	23	20

2.3.3.3 Emissions to water and soil

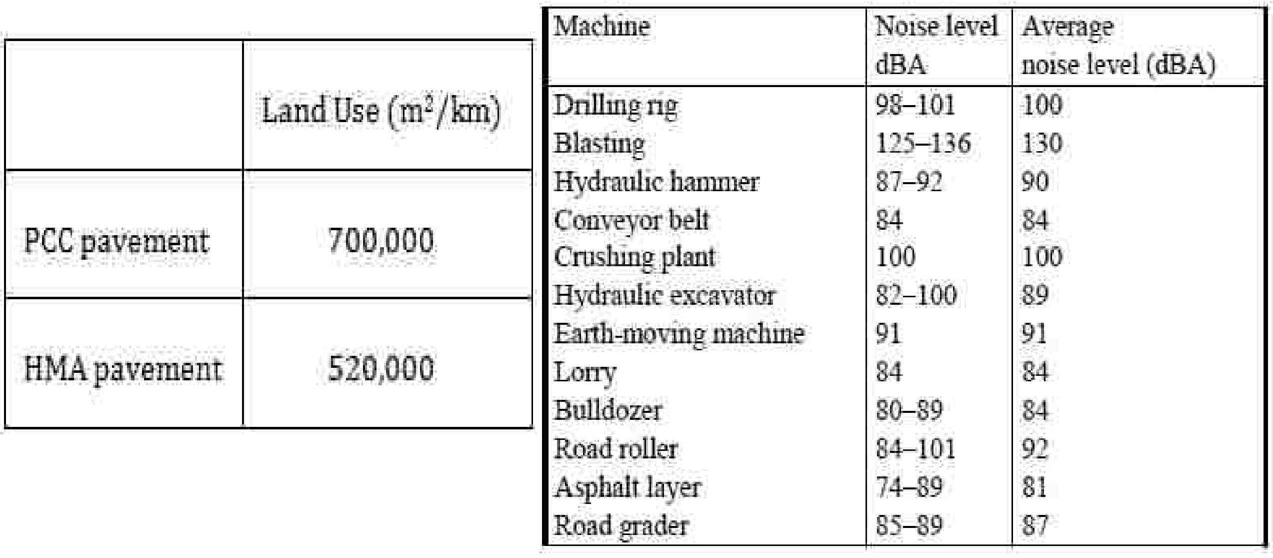
Eight of the 17 papers (32 assessments) estimated the emissions to water and soil. Horvath (2003, one assessment), Carpenter et al. (2005, two assessments), and Nathman et al. (2009, two assessments) used the LCA tool PaLATE, which can assess leachate, to evaluate water-borne and soil-borne environmental burdens, but they only specified Pb and Hg as water-borne emissions. In Häkkinen and Mäkelä's (1996) paper, emissions of heavy metals were assumed to be transferred to water based on the assumption that air emissions will fall as rain and, eventually, enter the aquatic system. In all, 24 emissions were assessed: Pb, Hg, As, Cd, Cr, N, Ti, Zn, phenol, P, COD, BOD, phosphates, HC, Cl^-, Cu, Ni, Ca, Na, Mn, Mo, S, Ba, and SO_4. The environmental impacts of these emissions were estimated: heavy metals were classified as the human health category, and P and phosphates adversely affected eutrophication. The same was found for airborne emissions, with not all emissions taken into account in every single assessment. General emissions to water and soil in the pavement LCAS, defined as those presented more than 10 times in pavement LCAs, are listed in Table 6.

Table 6 General Water-borne and Soil-borne Emissions in Pavement LCAs

Tally of water-borne emissions (32 in total)						
Pb	Hg	Cd	As	Cr	Zn	Cl^-
26	19	18	16	13	13	12

2.3.3.4 Noise

Häkkinen and Mäkelä (1996) considered noise disturbance during the "use" phase between different types of pavements, whereas Mroueh et al. (2000) compared noise during the construction phase. These were the only two pavement LCAs to consider noise. Häkkinen and Mäkelä (1996) dealt with noise in land use and measured the area around the road at which noise was higher than 55 decibels (dB), as shown in Figure 11(a). Mroueh et al. (2000) measured the noise level of work machines at a distance of 7 meters from the source. The results are shown in Figure 11(b).



(a)

	Land Use (m^2/km)
PCC pavement	700,000
HMA pavement	520,000

(b)

Machine	Noise level dBA	Average noise level (dBA)
Drilling rig	98–101	100
Blasting	125–136	130
Hydraulic hammer	87–92	90
Conveyor belt	84	84
Crushing plant	100	100
Hydraulic excavator	82–100	89
Earth-moving machine	91	91
Lorry	84	84
Bulldozer	80–89	84
Road roller	84–101	92
Asphalt layer	74–89	81
Road grader	85–89	87

Figure 11 Noise impacts (*Source*: [a] Häkkinen and Mäkelä, 1996; [b] Mroueh, et al., 2000)

2.3.4 Pavement LCA tools

Pavement LCA tools can facilitate the implementation of an LCA with less time and cost. Users only have to input project-specific data, such as pavement materials, dimensions, equipment types, and transport distance, etc. These tools usually do not require comprehensive knowledge about LCA and should be easy to use. However, with different scopes and concerns, the performance of these tools differs when assessing the same objects. Therefore, selection of an appropriate pavement LCA tool must be based on the users' goals and the limitations of that tool. From the reviews of Section 2.3.1 to 2.3.3, five pavement LCA tools/models were identified: PaLATE (Horvath, 2003), Mroueh's model (2000), Huang's model (2009), the eco-indicator (Chui, 2008), and

ROAD-RES (Birgisdóttir, 2005). The eco-indicator is excluded from the discussion due to the discordant output information (personal equivalents) compared with the other tools. These tools are evaluated from the perspectives of goal, scope, and data source. Three other tools, the BenReMod, PE-2 and OASIS, with no current peer-reviewed published pavement LCAs are also compared from the same perspectives.

There are other pavement LCA tools, but this research have attempted to review those available for public use or described in peer-reviewed journals. CHANGER, a GHG calculator developed by International Road Federation, is an example of proprietary models/tools.

2.3.4.1 PaLATE (Horvath, 2003)

Goal and scope: PaLATE, an Excel-based LCA tool, was developed on the basis of EIO-LCA for pavement construction. This model considers environmental impacts, as well as costs for selected functional units. As it is based on EIO-LCA, it does not assess the operation and use phases. The variables input by the user are the pavement's structure, duration of the analysis, transportation mode/distance, maintenance frequency, and equipment. The impact assessment includes the global warming potential (GWP), the acidification potential, and the human toxicity potential (HTP).

Data source: Figure 12 shows the life cycle phases and the corresponding data sources considered in PaLATE. Most material production data was obtained from the EIO-LCA model (CMU). Construction and maintenance activities were disaggregated into smaller processes, and these processes used the EIO-LCA, EPA database factor information REtrieval (FIRE), or EPA AP-42 data. The productivity, fuel type/combustion efficiency of the equipment and trucks were derived from the manufacturers' publications. Health impacts were assessed based on National Institute for Occupational Safety and Health (NIOSH) guidelines (Nathman, 2008). Therefore, PaLATE can be viewed as an I-O-based hybrid LCA tool.

Discussion: PaLATE can specify environmental impacts by phase of pavement life. In addition to environmental impacts, PaLATE can estimate life cycle costs for pavement projects. PaLATE also allows customization by allowing the user to input more accurate and specific data. On the other hand, PaLATE does not cover the operation and use phases. Due to using the I-O-based hybrid approach, the results suffered from double counting and is cannot account for imported goods. Moreover, the price data used to calculate the I-O data in PaLATE was for 1992, which is outdated and, in some cases, does not reflect the current economic relationship between sectors. Also, the calculation in the PaLATE spreadsheet contains numerous spreadsheet and data errors, thus the results unreliable. Nonetheless, PaLATE is perhaps the earliest attempt at a pavement LCA software tool for general use.

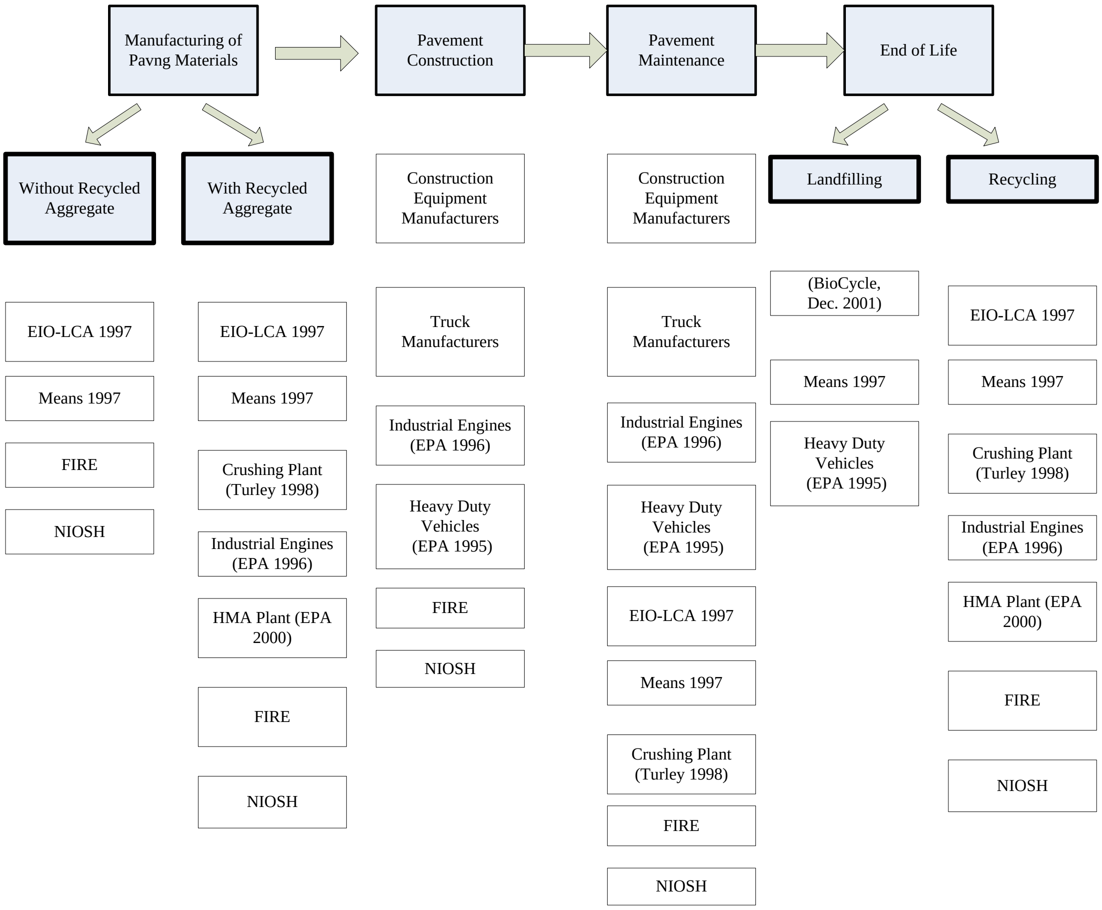


Figure 12 PaLATE data sources (Source: Horvath, 2003)

2.3.4.2 Mroueh's model (Mroueh et al, 2000 and 2001; Eskola et al., 2001)

Goal and scope: The Finnish National Road Administration conducted a process-based pavement LCA, considering material production, transportation, and construction for a 50-year duration. Pavement reuse and HMA rehabilitation were taken into account. Operational elements, such as traffic emissions, lighting, marking and road salting, were not included. The materials included in the scope were mainly by-products, such as FA, crushed existing concrete pavement, and BFS. These materials were used as sub-base materials for asphalt pavement in this model. The transportation mode was assumed to be trucks only. The machines were assumed to operate at average efficiency and to be used in normal summer conditions. The impact assessment in this model only included the LCI's calculation results, which included resource/energy consumption and various environmental loadings.

Data source: This model calculated the results of the LCA based on Finnish-based data, which were supplemented by international sources. Leaching data were obtained from laboratory-scale tests. Table 7 shows the principal data sources used in the LCA model of Mroueh et al.

Discussion: This model can specify environmental impacts for the assessed phases: production, transportation, construction, and use. These works were accumulated over several papers (Mroueh et al., 2000, 2001; Eskola et al., 2001). However, they did not result in a software package, and the reports lack application examples. The inventory data are also specific to Finland. Therefore, they may have limited applicability to other countries. The data inventory also lacked field measurements of dust emissions during construction and substances leaching.

Table 7 Principal Data Sources of Mroueh et al. (2000)

Work stage	Data source
Storing and loading of fly ash	Helsinki Energy (Oasmaa 1996)
Transport of fly ash and its placement into road constructions	Lohja Rudus (Rämö 1997)
Landfill disposal of fly ash	Helsingin Energia (Oasmaa 1996) Blomster 1989 City of Vantaa (Markkanen 1996) City of Helsinki (Arovaara 1996)
Blasting of rock	Lemminkäinen (Ruostetoja 1996)
Excavation of sand and gravel	Lohja Rudus (Rasimus 1996)
Crushing of aggregate	Lemminkäinen (Ruostetoja 1996) Finnra 1994 Finnra 1995
Transport of aggregate	Lohja Rudus (Rasimus 1998)
Road construction	RIL 156 1995
Blast furnace slag	SKJ-Yhtiöt (Mäkikyrö 1998)
Crushed concrete	Lohja Rudus (Määttänen 1998)
Cement	Häkkinen and Mäkelä 1996 Finncement (Lundström 1998)
Asphalt	Häkkinen and Mäkelä 1996 IVL (Stripple 1995)
Concrete	Häkkinen and Mäkelä 1996 Lohja Rudus Oy (Kostiainen 1999)
Lime	Häkkinen and Mäkelä 1996
Lumber	Häkkinen et al. 1997
Reinforcing steel	Häkkinen and Mäkelä 1996
Repaving	Finnra (Komulainen 1998)
Remixing	Finnira (Eerola 1998) Design of pavements/ Finnra 1997 Elg-yhtiöt (Elg 1998) JJ-Asfaltti Oy (Karvonen 1998) Valtatie Oy (Mannonen 1998) VTT Chemical Technology (Siltanen 1998)
Tack-coating	VTT Building Technology (Apilo 1998)
Deep stabilisation	Betoni-Tekra Oy (Pietikäinen 1999) Junttan Oy (Sohlman 1998)
Vertical drainage	Kaitos Oy 1998 Geotechnics Holland BV 1998 Containerships 1998
Leaching of impurities	VTT Chem. Technology (Wahlström et al. 1999)

2.3.4.3 Huang's model (Huang et al., 2009a)

Goals and scope: Huang's model is an Excel-based LCA tool, which has been developed for construction and maintenance of HMA pavements in the U.K. This model is built on a PLCA approach and considers material production, transportation, construction, maintenance, and end-of-life phases. The impact assessment includes GWP, acidification, photochemical smog, human toxicity, eco-toxicity, noise, landfill, and eutrophication.

Data source: Most data used in this model's inventory are from U.K. plants and contractors and European averages, and the data are specific to Europe. Table 8 shows some data sources used in this model.

Table 8 Principle Data Sources of Huang et al. (2009a)

Process	Data source
Electricity production	EURELECTRIC (1998)
Diesel production	IVL (2005)
Other energy production	NAEI (2005); US DOE NCSA; Canadian NRC
Fuel combustion	EEA's EMEP/CORINAIR (2005)
Transportation and operation of construction vehicles	EU emission limits (2005) IVL (2005)
Materials' production	Contractors
Fuel efficiency of transport vehicles	Contractors

Discussion: Huang et al. (2009a) focused on identifying the most relevant, adaptable, and available data for U.K.-specific pavement LCAs. Owing to being the most recent model, which most complies with the ISO standards, this model only assessed environmental impacts for the entire life cycle; impacts from individual phases were not available. This model is not publically available. Thus, it is difficult to further study the model's structure and data.

2.3.4.4 ROAD-RES (Birgisdóttir et al., 2005, 2006, 2007)

Goals and scope: ROAD-RES was developed to analyze municipal solid waste incinerations (MSWI) as materials for pavement sub-base construction in Denmark. This model compared MSWI to landfill deposit and virgin materials for pavement sub-base. The structure of the model is shown in Figure 13. Construction, operation, and maintenance phases were taken into account. The life span was 100 years, with maintenance for wearing courses every 20 years and base courses every 40 years. Maintenance, such as salting and snowplowing, was included. ROAD-RES also focuses on leached constituents such as heavy metals and salt to air, soil, and water. Environmental impact categories such as eco-toxicity$_{\text{water/soil}}$ ($E_{w/s}$), nutrient enrichment (NE), and stored eco-toxicity$_{\text{water/soil}}$ ($SET_{w/s}$) were compared.

Data source: Information on the production of the materials and on the construction of the equipment was collected from Danish plants and producers. All leaching data were based on laboratory tests. RoadRes used Stripple (2001) as source for those processes of which data are unavailable from Danish sources. Details of the data sources were not specified in this model.

Discussion: Data transparency might be an issue using this Danish-specific model. The maintenance cycles' estimates were based on replacing the wearing course every 20 years and replacing the base course every 40 years. The impacts in ROAD-RES were normalized by one person per year in person equivalents (PE), of which the definition details were not specified, making it difficult to make a comparison with other LCA research. This model only assessed environmental impacts for the entire life of 100 years. Impacts from individual phases were not available. This model is not publically available.

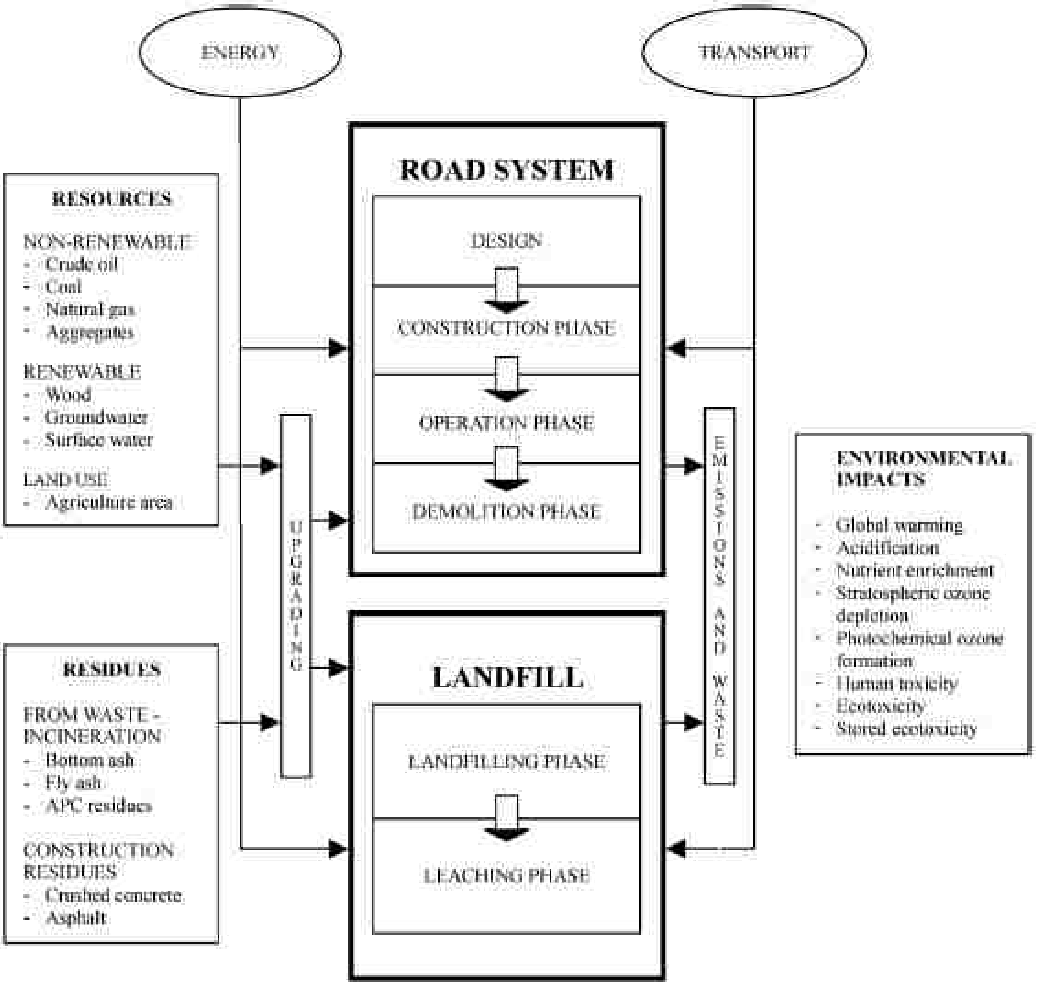


Figure 13 Structure of the ROAD-RES model (*Source*: Birgisdóttir et al., 2006)

2.3.4.5 Other tools

2.3.4.5.1 BenReMod-LCA (Apul, 2007)

Goals and scope: The BenReMod-LCA (beneficial reuse modules), a web-based module, has been developed to evaluate and quantify environmental impacts of recycled materials and industrial by-products. In this module, only "materials production" and "transportation" phases in the pavement lifecycle are considered, thereby making it difficult to compare this model with the other models. Another significant assumption is that coal combustion is the only electricity source in the U.S.

The impact categories GWP, acidification potential (AP), HTP, fresh aquatic eco-toxicity potential (FAETP), fresh sediment eco-toxicity potential (FSETP), and terrestrial eco-toxicity potential (TETP) were used to index the environmental impacts. RAP, recycled concrete pavement (RCP), steel slag, FA, and bottom ash were the available recycled materials in this module. Raw materials included natural aggregates, lime, cement, and asphalt. The module allows users to compare different scenarios by inputting the intended percentages of the composed materials. The BenReMod-MCDA includes an enhancement called a multi-criteria decision-making tool, which is intended to help decision makers to rank possible scenarios. The BenReMod-MCDA automatically takes account of the outputs from the BenReMod-LCA, and then the users have to assign weights to the above-mentioned impact categories.

Data source: To avoid data uncertainty from aggregation and errors from converting economic activities to environmental impacts, BenReMod uses process-based data (Stripple, 2000, 2001; Spath et al., 1999), FIRE, and various laboratory tests.

Discussion: Data uncertainties exist relating to leachate, and impact characterizations need to be further modified. The system's boundary does not include the "construction" and the "maintenance/repair" stages. This model is available to the public at: https://benremod.eng.utoledo.edu.

2.3.4.5.2 Project-emission estimator (PE-2) (Mukherjee, 2012)

Goals and scope: PE-2 is a web-based tool to estimate carbon dioxide emissions for pavement construction at the project level. PE-2's system's boundary includes the production of the materials, transportation, construction, use, and maintenance; however transportation is not calculated individually but integrated in material production. Carbon dioxide emissions are the only environmental impact category.

Data source: PE-2 is a hybrid LCA tool. Data on the production of materials are derived from both EIO and process-based data. Data on construction and maintenance equipment were collected from existing literature in the field and from historic databases. More specific data sources for individual processes need to be identified for further validation. Emissions during the "use" phase, due to traffic delays, and reroutes during construction were considered using the MOVES simulation package.

Discussion: PE-2 includes many materials and a range of equipment, but it usually only uses one data point for several similar materials or types of equipment. Data sources for individual processes need to be identified specifically for better data transparency. PE-2 is available to the public at: http://www.construction.mtu.edu:8000/cass_reports/webpage/.

2.3.4.5.3 Operation for Safe, Intelligent, and Sustainable Motorways, OASIS (González and García, 2009)

Goals and scope: OASIS is a Spanish program aimed at calculating energy and greenhouse gases during pavement construction and maintenance. It includes the production of the materials, transportation, construction, maintenance, and end-of-life.

Data source: The energy and CO_2 emissions involved in the initial construction of the pavement and the production of the materials were based on a Spanish database called ITEC-BEDEC (Institut de Tecnologia de la Construccio de Catalunya. This database was built in collaboration with the Catalan Institute of Energy (ICAEN), the iMat Construction Technology Center, and the Polytechnic University of Catalonia. The information was based on European databases (the Ecoinvent 1.3 Inventory of Carbon and Energy (ICEO), the Construction Industry Research and Information Association (CIRIA), the Institute of Environmental Sciences (CML), and the Instituto de Diversification y Horror Energético (IDAE). The calculation methodology was based on

Sima pro 7.0. The information was obtained from product manufactures, companies, and technical specifications.

Discussion: Publications and information on OASIS are still limited. OASIS is not available for public use, and there is no English version.

2.3.5 Comparison of pavement LCA results

This research compares results of the 17 papers (66 assessments as shown in Table 4) on energy consumption and CO_2 emissions. The selected assessments were divided into two groups based on the LCA approaches used: a pure process-based group containing 46 assessments and an EIO-based group (EIO-LCA, I-O-based hybrid, and tiered hybrid) containing 20 assessments. These assessments covered and interpreted various environmental impacts and energy/material inputs in the pavement's life cycle. Among those burdens, energy consumption and CO_2 emissions were the most common outputs in existing pavement LCAs (61 assessments of energy usage and 47 of CO_2 emissions). Therefore, the reported unit consumption of energy and the CO_2 emissions in the selected assessments were compared for the process-based and the EIO-based group.

Table 9 and Table 10 depict pavement types and the energy usage and the CO_2 emissions amongst the two groups. Use (traffic) and operation phases were not included. The energy usage and the CO_2 emissions were expressed in unit value (per lane-mile, defined as a lane width of 12 feet) through the assumed service life, 40 or 50 years.

Table 9 LCA Results of The Process-based Group (*Source*: Muench et al., 2010)

Sources	Pavement's features	Unit's energy consumption (GJ/lane-mile)	Emissions-CO2 (Mg/lane-mile)
Athena Institute (2006)	Art-PC-CBR3	3.33E+03	4.08E+02
	Art-AC-CBR3	5.94E+03	4.36E+02
	Art-PC-CBR8	3.04E+03	3.77E+02
	Art-AC-CBR8	5.40E+03	3.92E+02
	HV-PC-CBR3	4.42E+03	5.06E+02
	HV-AC-CBR3	7.92E+03	5.79E+02
	HV-PC-CBR8	4.12E+03	4.75E+02
	HV-AC-CBR8	7.31E+03	5.29E+02
	Quebec- PC	6.06E+03	7.93E+02
	Quebec-AC	1.10E+04	7.13E+02
	Ontario-PC	6.07E+03	6.48E+02
	Ontario-AC	8.34E+03	6.01E+02
Stripple (2001)	HMA-Hot	4.77E+03	8.85E+02
	HMA-Cold	4.54E+03	8.58E+02
	PC	6.56E+03	1.22E+03
Häkkinen and Mäkelä (1996)	PC-main A	3.60E+03	4.82E+02
	PC-main B	3.62E+03	4.83E+02
	AC-main A	6.00E+03	2.01E+01
	AC-main B	1.06E+04	2.22E+01
Mroueh et al.	FA1	4.16E+03	4.41E+02

Sources	Pavement's features	Unit's energy consumption (GJ/lane-mile)	Emissions-CO2 (Mg/lane-mile)
	FA2	3.53E+03	3.53E+02
	FA3	2.97E+03	2.72E+02
	CC1	3.25E+03	2.93E+02
	CC2	2.24E+03	2.06E+02
	BFS	3.00E+03	2.65E+02
	R1	3.28E+03	2.98E+02
Huang (2009a)	HMA-virgin	3.05E+03	6.97E+02
	Glass, RAP, IBA in HMA	2.98E+03	6.82E+02
	RAP, IBA in HMA	2.93E+03	6.70E+02
	Glass, RAP in HMA	3.00E+03	6.86E+02
	Glass, IBA in HMA	3.08E+03	7.07E+02
Huang (2009b)	HMA	2.14E+03	2.23E+02
Chui et al. (2007)	HMA	2.17E+03	N/A
	RAP	1.85E+03	
	AR-HMA	1.57E+03	
	Glassphalt	2.61E+03	
Zapata and Gambatese (2005)	CRCP	3.75E+03	N/A
	HMA	3.09E+03	
Weiland (2008)	PCC	4.05E+03	5.25E+02
	HMA	6.22E+03	3.43E+02
	CSOL	3.46E+03	1.91E+02

PC/PCC: Portland cement concrete pavement; AC/HMA: asphalt concrete pavement; ART: arterial HV: high volume; AC-Hot: hot mixed AC; AC-Cold: cold mixed (emulsified) asphalt; main A/B maintenance plan A/B; FA: fly ash; CC1: crushed stone; BFS: burst furnace slag; R1: natural aggregate only; HMA: hot mix asphalt; RAP: recycled (reclaimed) asphalt pavement; IBA: incinerator bottom ash; glassphalt: HMA with glass as fine aggregate; CRCP: continuous reinforced concrete pavement; CSOL: crack, seat and overlay

For the process-based group, the maximum, minimum, and average unit energy usage/CO_2 emissions for HMA and PCC are showed in Figure 14. Some papers conducted more LCAs than others. Thus, the figure is likely skewed towards those papers that conducted the majority of LCAs: most notable are Athena (2006) and Mroueh et al. (2000). Average energy and CO_2 for HMA and PCC were close but HMA showed larger variances in energy usage. Another noticeable issue about energy is feedstock energy. ISO 14044 requires feedstock energy to be considered in LCAs, although feedstock energy in bitumen is yet undecided whether bitumen should be viewed as a source of energy (Santero, 2009). The feedstock (inherent) energy used in the process-based studies (Athena, 2006; Stripple, 2001; Häkkinen and Mäkelä, 1996) ranged from 5.61 to 42 MJ/kg. The average unit energy usage was 2.04×10^4 GJ/lane-mile, which is 216% higher than the value (6.38×10^3 GJ/lane-mile) without considering feedstock energy.

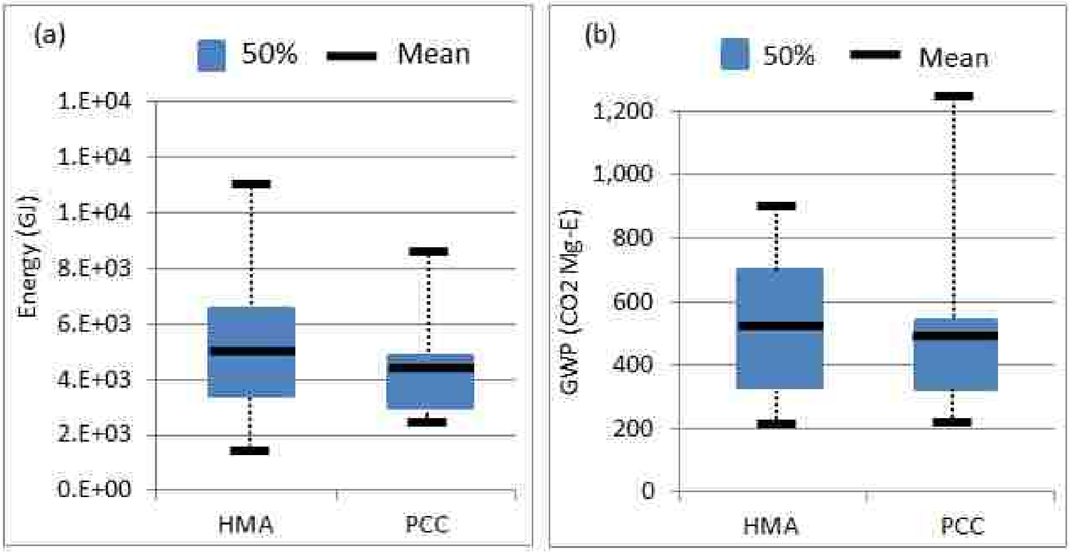


Figure 14 Box plot of (a) Energy and (b) CO_2-E emissions for process-based LCA

Table 10 Results of LCAs of EIO-based Group (*Source*: Muench et al., 2010)

LCA type	Tool	Sources	Pavement's features	Unit's energy consumption (GJ/lane-mile)	Emissions (Mg/lane-mile) -CO_2
EIO-LCA	N/A	Horvath and Hendrickson (1998)	HMA	5.64E+03	N/A
			CRCP	4.03E+03	
IO-based hybrid	PaLATE	Horvath (2003)	RAP	1.75E+04	N/A
		Carpenter et al. (2007)	HMA-natural	6.26E+03	3.81E+02
			HMA-BA	3.54E+03	1.88E+02
		Uzarowski et al. (2008)	Conventional HMA	2.32E+04	1.31E+03
			Perpetual	1.58E+04	8.93E+02
		Alkins et al. (2008)	HMA Mill/overlay	N/A	1.61E+02
			CIR		7.77E+01
			CIREAM		7.38E+01
		Nathman et al. (2009)	Asphalt emulsion	1.13E+03	6.42E+01
			Ultrathin HMA	3.71E+02	2.75E+01
			RAP	1.49E+02	1.50E+01
			RAP with crumbed rubber	8.58E+02	2.60E+02
			CIR	1.51E+01	1.10E+00
Tiered	N/A	Treloar	CRC	2.09E+05	N/A

LCA type	Tool	Sources	Pavement's features	Unit's energy consumption (GJ/lane-mile)	Emissions (Mg/lane-mile) -CO_2
			PC	1.55E+05	
			FDA	3.01E+05	
			Comp	2.32E+05	
			DAS	2.09E+05	
			G	6.52E+04	
			DSAB	1.99E+05	
			ACB	1.21E+05	

HMA: hot mix asphalt; CRCP/CRC: continuous reinforced concrete pavement; BA: bottom ash; CIR: cold in-place recycling; CIREAM: cold in-place recycling expanded asphalt mix; RAP: recycled (reclaimed) asphalt pavement; FDA: full depth asphalt; Comp: composite, asphalt and concrete; DSA: deep strength

For the EIO-based group, the maximum, minimum, and average unit energy usage/CO_2 emissions for HMA and PCC are showed in Figure 15. There was no available data for CO_2 emission for PCC in EIO-based LCA. The results of Nathman et al. (2009) and Alkins et al. (2008) were excluded because the materials and construction activities relating to pavement maintenance (cold in-place recycling) was significantly different from regular pavement construction (mill and fill). The result is showed as "HMA adjusted" in Figure 15.

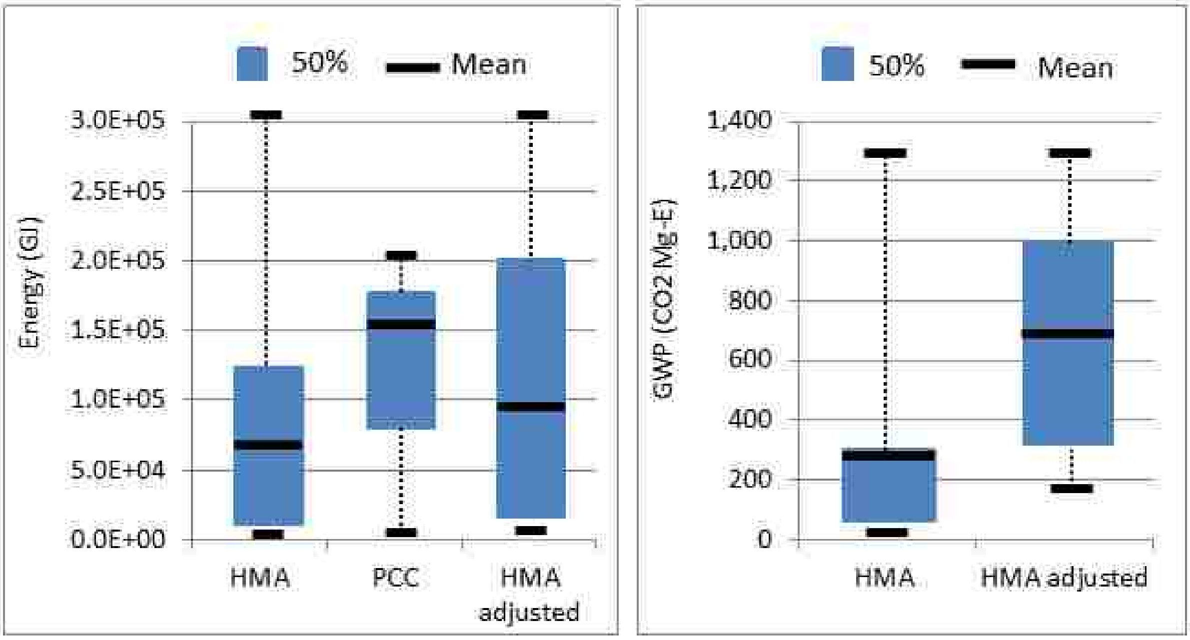


Figure 15 Box plot of energy and CO_2-E emissions for EIO-based LCA

In the EIO-based group, only two papers (Horvath and Hendrickson, 1998; Treloar et al., 2004) compared the energy usage of HMA and PCC pavements, and both of these showed that HMA pavements consume more energy than PCC pavements. There was no HMA/PCC comparison on CO_2 in the EIO-based papers.

2.3.6 Conclusions for pavement LCAs and pavement LCA tools

Common practices in pavement LCAs are listed in following perspectives:

1) Lifecycle phase: the production of the materials, transportation, construction, and maintenance were commonly considered. Only a few (4 of the 17 papers) studies incorporated the use phase (traffic) into their scopes.

2) Functional unit: with a certain length and a certain number of lanes, a pavement that serves for 40 or 50 years is most common.

3) Materials: Bitumen, cement, aggregates, steel HMA mixing, and PCC mixing were the major material processes taken into account.

Process-based pavement LCAs play a more significant role in pavement research by numbers of publications. Activities during the life cycle can be described by processes and data corresponding to the specific processes, and the specific data can form a superior life cycle inventory. However, a large amount of time and cost might be spent on a process-based LCA for complicated products, in which the system’s boundaries need to be carefully determined. Only one study adopted the EIO approach (Horvath and Hendrickson, 1998). In this study, the authors mentioned that the data quality of the study caused concerns due to the data sources used.

Hybrid pavement LCAs, which combine the advantages of both approaches, were used in Treloar et al. (2004) and studies applied PaLATE. However, they did not address operation and use phases, and inventory structure and calculation details were unavailable. Furthermore, the problem of the double counting of the data was difficult to deal with. Therefore, among these LCA approaches, process-based analysis was selected for this research. First, more specific results can be achieved by this method.

Second, there are more results available for comparison and validation. Although data collection is an issue, this problem can be addressed by drawing a reasonable system boundary and building a U.S. specific database for pavement construction.

Several tools were published to conduct pavement LCAs: PaLATE, Mroueh's model, Huang's model, ROAD-RES, and BenReMod-LCA. Each of these tools has its own strengths and weaknesses. Table 11 summarizes LCA type used, availability to public, and scope coverage of these tools as well as Roadprint, the tool developed by this research. Uncertainty coverage is also listed in this table. Uncertainty issues in LCA will be addressed in next section, Section 2.4.

PaLATE contains a database for equipment and environmental burdens, but the results from the I-O-based hybrid approach can result in concerns of double counting and data quality.

Mroueh's model can address environmental burdens for each life cycle phase, thereby facilitating improvements in specific procedures. However, the software package is currently unavailable.

Huang's model complies with ISO standards, but it is U.K. and Europe oriented. Although this model includes material production, transportation, construction, and maintenance, it only generates LCIA results for whole life cycle. Huang's model is not available to public.

ROAD-RES is very specific in addressing leaching; however, the normalized unit in ROAD-RES, the PE, is not well documented in the literature, making it difficult to validate the results of ROAD-RES.

Three other tools with limited peer-review publications were also discussed: BenReMOD, OASIS, and PE-2. The BenReMod excludes two life cycle phases: the construction phase and the maintenance phase, which may or may not be significant, thus limits the capability and results. OASIS currently has limited publications and information, thus results in transparency issue. OASIS is not available to public. PE-2 only provides CO_2 emission, which is insufficient to assist decision making.

Table 11 Tool Comparison on LCA Type, Availability and Scope

Tool	**LCA Type**	**Available to Public**	**Scope**							
			Material Production	**Transportation**	**Construction**	**Maintenance**	**Use**	**End-of-life**	**LCIA**	**Uncertainty**
PaLATE (Horvath, 2003)	Hybrid LCA	V	V	V	V	V		V	V	
Mroueh's Model (2000)	PLCA		V	V	V		V			
Huang's Model (2009)	PLCA		V	V	V	V		V	V	
Road-Res (Birgisdóttir et al., 2005)	PLCA		V		V	V	V	V	V	
BenReMod (Apul, 2007)	PLCA	V	V	V					V	
OASIS (González and García, 2009)	PLCA		V	V	V	V		V		
PE-2 (Mukherjee, 2012)	Hybrid LCA	V	V		V	V	V			
Roadprint	PLCA	V	V	V	V	V		V	V	V

2.4 Uncertainty in LCA

The results of an LCA are deterministic. However, LCAs are intrinsically probabilistic given variations in system boundaries, subjective choices, assumptions, accuracy of available data, and uncertainty in the result of impact analysis (ISO, 1997). The uncertainty and the variability in LCA can be classified as (1) parameter uncertainty, (2) model uncertainty, (3) uncertainty due to choices, (4) spatial variability, (5) temporal variability, and (6) variability between objects and sources (Huijbregts, 1998). It would be helpful to implement uncertainty and variability analysis for LCA models to better serve decision makers judging the results of LCAs.

Parameter uncertainty, which is caused by data inaccuracy or lack of data, generally contributes the most to result uncertainty. Various methods have been proposed to fathom uncertainty due to a lack of data, including analytical uncertainty propagation, stochastic modeling, fuzzy logic computation, and Bayesian statistics (Hoffman et al., 1995; Heijung, 1996; Kennedy et al., 1996; Becalli, 1997; Peterson, 1997). For available data, stochastic modeling is viewed as the most promising tool, and Monte Carlo simulation is the most common way to perform stochastic modeling. To reduce parameter uncertainty, however, more reliable data must be measured and obtained.

Other uncertainties are more subjective, caused by how the model is built, how the system boundary is drawn, which unit processes are included, and which data point to use. These types of uncertainty are usually acknowledged when comparing LCAs that use different model, however they are not quantified. Scenario analysis, standardization, and expert judgment are available tools to address these types of uncertainties.

Uncertainty is rarely included in pavement LCAs and none of the 66 pavement LCAs reviews had taken uncertainty into account. However, uncertainty analysis is useful in a LCA tool as it would help confirm the validity of results. Therefore this research proposes to use Monte Carlo simulation to address parameter uncertainty as a start of considering uncertainty for pavement LCA.

2.5 LCA and pavement LCA summaries

In this chapter, the framework of LCA was introduced: including setting the assessment's goals; the system's boundary is based on the definition of the scope; a data inventory is then built; the last step is to interpret the results by impact assessment.

Three major approaches—process-based LCA, EIO-LCA and hybrid LCA—to implement LCAs were reviewed and compared. Process-based LCA can be more precise, specific, and up-to-date; it also requires more time and incurs higher costs to build a functional data inventory. On the other hand, the EIO-LCA can save time and costs, but it suffers from reduced specificity and data quality. The hybrid LCA, which uses partially process-based data and EIO data, potentially offers the advantages of the two approaches, but it also features the downsides of both approaches.

The process-based was selected for use in Roadprint since process-based approach allows practitioners to more precisely define a specific paving project, which is useful in comparing alternatives or taking into account local variables such as energy mix, haul distance, equipment use, and mix design.

In this chapter, unit processes that have been considered in pavement LCAs were listed and discussed under the following categories: energy production, production of materials, construction equipment, transportation, and environmental impacts. Existing pavement LCA models/tools were also compared and investigated. Based on the discussions, a pavement LCA should be able to address the following issues:

1) identify U.S.-centric data sources to the extent possible
2) address the following phases: materials production, construction, maintenance, transportation

3) generate results for entire lifecycle but also able to be deconstructed into different phases
4) be consistent with existing practice to the extent possible
5) be transparent: practitioners should be able to see and modify the data sources and calculations if they wish
6) address parameter uncertainty in the pavement LCA

Chapter 3. Methodology and Tool-Building Procedure

Based on the aforementioned literature and discussions, a pavement LCA tool, Roadprint, is proposed to quantitatively evaluate the environmental impacts of a pavement project. This tool will apply the process-based LCA approach and contain an appropriate LCI database. Construction productivity will also be simulated in order to produce more accurate equipment use inputs. This tool is intended to serve as an environmental decision-making support mechanism during project planning and development phases. This chapter describes the framework, data sources and the development process of Roadprint.

Section 3.1 to 3.7 describes the Roadprint tool development including goal, scope, data sources, inventory calculation method, LCIA, productivity simulation, and parameter uncertainty. Section 3.8 provides an overview of the tool, including user-entered input parameters and result outputs.

The goal of this tool is to allow pavement practitioners who do not have specialized LCA knowledge or resources, conduct a pavement LCA and obtain acceptable results using inputs typically available to them in a reasonable timeframe. User inputs are pavement parameters and construction parameters, such as dimensions, pavement types, and materials/equipment used, all of which are either known to or can be readily estimated by users. The values of other necessary inputs for inventory calculation, such as energy requirements and emissions from material production, are automatically retrieved from a built-in pavement LCI database. A checklist developed by the University of California Pavement Research Center (UCPRC, 2011) is used to document Roadprint in an effort to provide a standard catalog of its elements (please see Appendix B).

3.1 Goal

The goal of implementing pavement LCAs is to comprehensively understand the burdens of HMA or PCC pavement construction for a specific project. Natural resources/energy consumptions and environmental impacts are expected outputs, which can be used to support decision making.

3.1.1.1 Functional unit and functions

The pavement's functional unit is used to serve regular vehicle traffic for a set duration with a required service level. Therefore, the structure of the functional unit involves a predicted traffic level, desired life (in years), and a performance standard. The design of the pavement structure usually takes traffic volume, expected service life, and desired performance into account. For example, AASHTO (1993) requires predicting traffic (equivalent single axle load (ESALs) can be converted from traffic volume and composition) and the serviceability index (Pavement Service Index) as pavement design inputs. The real functional unit will be determined by the users' inputs of the pavement structure and the construction parameters for different scenarios.

3.1.1.2 Common and distinct unit processes

HMA and PCC LCAs share some unit processes such as site preparation, energy production, and transportation (Stripple, 2001; Weiland, 2008; Pavement Interactive, 2010). Site preparation includes sub-base grading, and compaction energy sources include electricity and fuel. Electricity is used for operating facilities and for the equipment involved in raw material extraction, manufacturing, and construction. Fuel is used for all transport processes and also operating construction equipment. Transportation unit processes are the same, regardless if the process is for HMA or PCC LCAs.

In addition to common shared processes, HMA LCAs have distinct unit processes separate from PCC LCAs. The unit processes of HMA LCAs that are not shared with PCC include:

1) HMA production: aggregate/bitumen production, HMA mixing
2) HMA paving: material transfer vehicles(MTVs) and paver operation
3) HMA finishing: breakdown rolling, finishing rolling
4) Maintenance: crack sealing, patch repairs, surface milling, and CIR

The distinct unit processes in PCC LCAs include:

1) PCC production: aggregates/cement production, PCC mixing
2) PCC placement: PCC placing, spreading, and paving
3) Finish: texturing, curing, and saw-cutting

3.2 Scope and system boundary

In this tool, three life phases are included: material production, transportation, construction (including maintenance and end-of-life). This tool encompasses resource inputs (raw materials), environmental outputs (air emissions), material production, transportation, and construction activities that required for the three phases are all included in the LCA scope.

The following are the input and output data that need to be identified for the LCI database.

1) Energy production: electricity and fuel production
2) Transportation activities: truck hauling, sea freight, and locomotive transportation
3) Production of bitumen: crude oil extraction, transportation, and refining

   Feedstock energy will be included in the scope. However, whether asphalt can be viewed as a source to generate energy in general practice is still controversial (Santero, 2009). Therefore, feedstock will be processed as an additional option when computing the LCA results.

4) Production of cement: extraction, transportation, and manufacture
5) Production of aggregate: rock/sand extraction, crushing, and transportation
6) Production of steel: for dowel/tie bar production
7) Production of HMA/PCC: mixing plant operation
8) Aggregates/cement alternatives: waste glass, used rubber tires, crushed concrete waste, BFS and fly ash, bottom ash, and RAP are all taken into account. HMA milling is deemed as the production of RAP. PCC demolition is deemed as the production of crushed concrete waste. For other materials, only transportation processes are included.
9) Equipment operations: The energy consumption and emissions of all the equipment involved in pavement construction will be studied. Equipment includes excavators, rollers, pavers, breakers (hammers), milling machines, trucks, concrete mixing trucks, railway locomotives, hot mix asphalt plants, and Portland cement concrete plants.

There are certain processes that are insignificant or where it is difficult to obtain valid data. Thus, these are not included in the system boundary. These processes include:

1) Use and operation: Use (traffic and pavement condition) and operation (signage, street lighting, traffic control, and striping, etc.) phases are not considered in this proposed pavement LCA. The traffic, lighting, and traffic control that operate on a pavement over its life can be the largest contribution to consider in pavement LCA (Santero 2009). However, they are highly uncertain, and such uncertainties would likely overwhelm any other calculations. Signage and striping can be ignored because it accounts for only about 0.0038% of CO2 and 0.013% of energy consumption during HMA pavement construction (Stripple, 2001)

2) Manufacture of vehicles, equipment, and plant. To avoid an unmanageable inventory and results that are not focused on pavement construction, the assemblage or fabrication of vehicles, equipment, power plants, and mixing plants are not included.

3) Production of crumb rubber, fly ash, bottom ash and slag. The productions of used rubber tires, bottom ash, fly ash, and BFS are viewed as industrial by-products. It is difficult to obtain data for solely producing those materials. Hence, the production processes of these selected aggregate/cement substitutes are beyond the scope of this study.

4) Uncommon processes. These processes were rarely covered in pavement LCAs, and existing data has quality concern. Therefore, leaching and noise are not included in the system boundary. The water usage and environmental impact of solid waste are also excluded for the same reason.

Figure 16 shows the system boundary, which takes into account the unit processes, scope, and exclusions, according to the elements in UCPRC checklist. All modes of transportation within the system boundary are included.

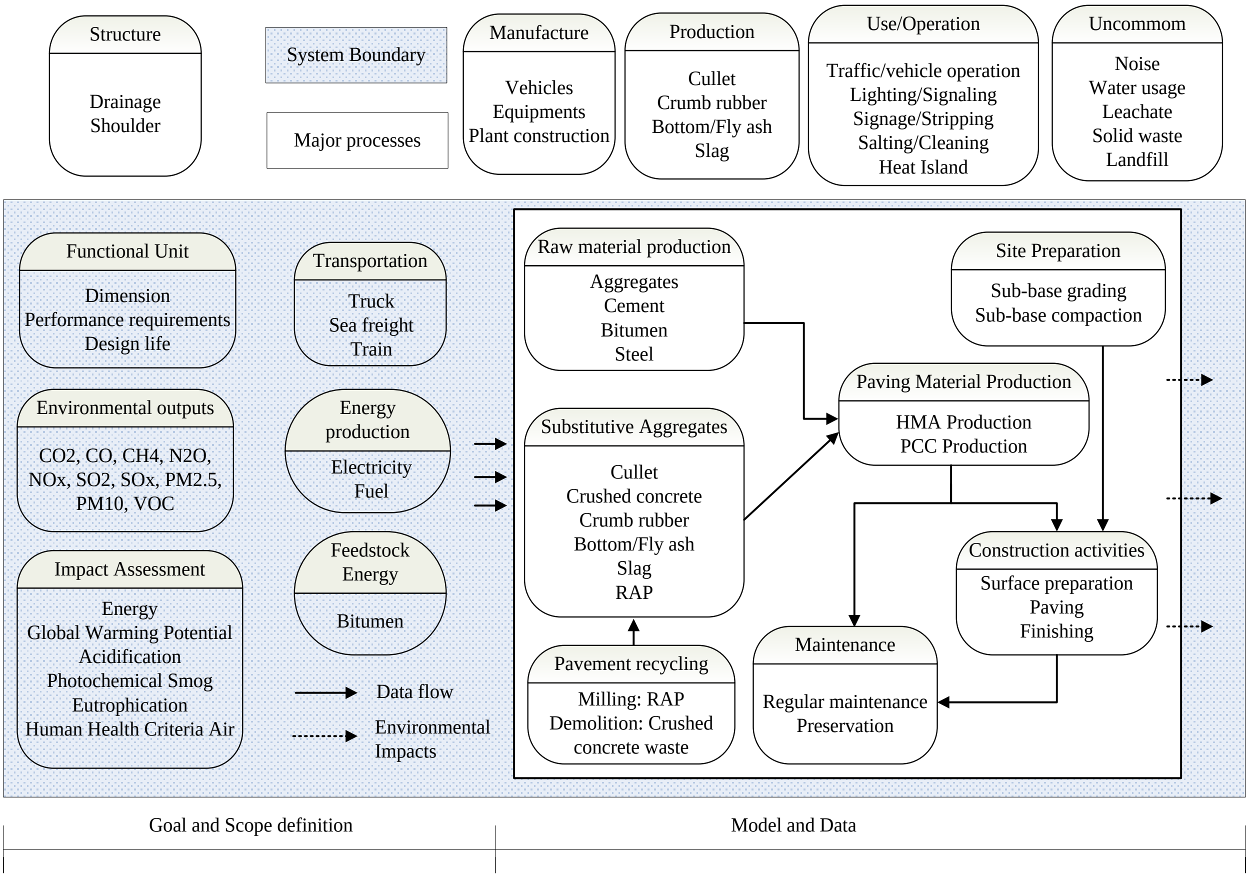


Figure 16 System boundary of proposed LCA model

3.3 Data sources and default value assessment

In this section, the availability and quality of data in all process-based references are assessed. According to the discussion in Section 2.1 and Section 2.2, IO-base data are considered less appropriate and consequently are excluded here. Data quality is required to be assessed from the guidelines of time-related coverage, geographic coverage, precision, completeness, representativeness, consistency and reproducibility (ISO 14044, 2006). In this research data quality is assessed based on a point based system following the guidelines shown in Table 12. This 5-point scoring mechanism is based on the numeric scores method described in Cooper and Kahn (2012). The data sources for default values are chosen mainly on the qualities of two data points: energy consumptions and CO_2-E emissions, because energy is currently the most desirable input, and CO_2-E is the major contributor of the most desirable output, GHG.

More accurate outputs are obtained using data with better data quality (defined as having higher score based on the guidelines in Table 12), and the identified data are used as default values in the LCI database of Roadprint. However, the LCI database can be updated since Roadprint allows users to modify or replace existing data with different data to observe trends, variations, and improvements.

Table 12 Data Quality Guidelines (Derived From Cooper and Kahn, 2012)

Data Quality Category	Best (5)	Worst (1)
Time related coverage	Less than 5 years old	More than 20 years old
Geographic coverage	Site specific; US centric	Data from location with different conditions and countries
Precision, completeness and representativeness	All emissions, all assumptions correct	Missing data, incorrect assumptions, inaccuracies
Consistency and reproducibility of methods used	Data from accepted test methods, steps understood, reproducible	Data acquisition methods unknown, difficult to reproduce

Sometimes there are no available data for necessary unit processes that should be included in the system boundary. These processes are currently viewed as "free processes," which means they contribute to other process but will not have any energy and emissions impacts. This type of process makes the system boundary more complete and makes future modification easier. However, LCA results will also be affected because they do not contain any energy and emission data.

3.3.1 Bitumen production

Available data and sources: data for bitumen production can be found in IVL (Stripple, 2001), VTT (Häkkinen and Mäkelä, 1996), Athena (2006), Eurobitume (2011).

Selected data source: The data used is derived from the report by Eurobitume (2011) and included paving grade bitumen, polymer modified bitumen (PMB) and bitumen emulsion. Data quality score is shown in Table 13.

Table 13 Bitumen Production Data Quality Score

Category	Score	Overall Score
Time	5	3.5
Geography	1	
Precision, completeness	5	
Consistency and reproducibility	3	

Strength: This data is the most updated, and it also features detail description of the system boundary, the transparency of the calculations, and its data sources. Figure 17 shows the system boundary used in the Eurobitume report.

Weakness: The composition of the crude oil used in bitumen production in the U.S. is different from Europe. The mode and distance of transportation used to transport the bitumen is also different. However these two facts are ignored and this data is selected in this study due to a lack of better data sources for bitumen production of U.S.

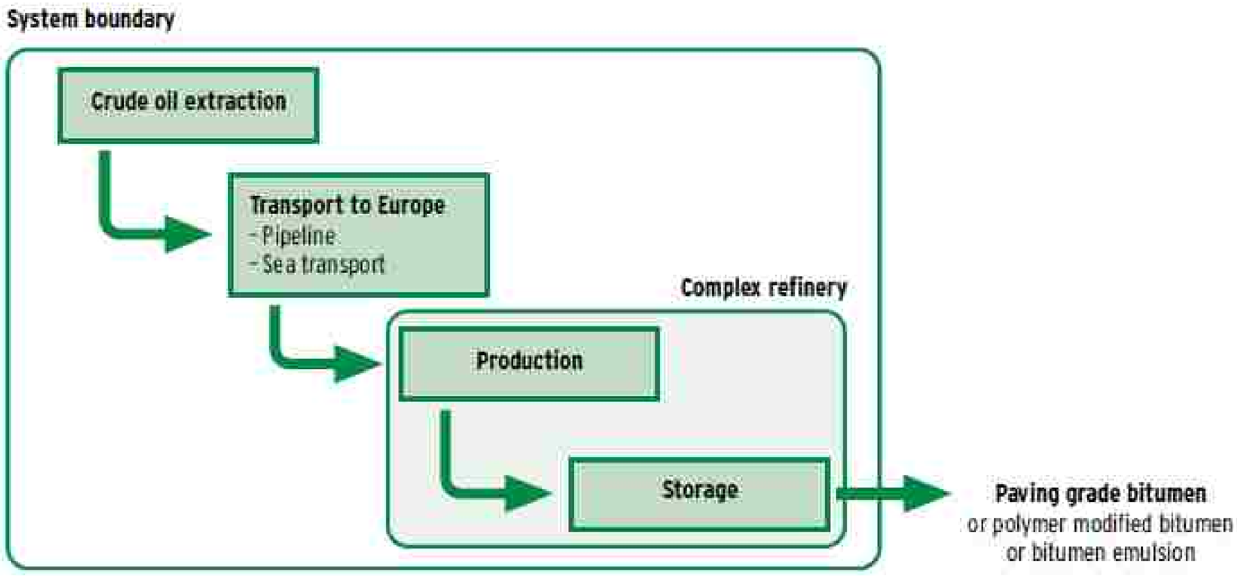


Figure 17 Flow chart and system boundary for bitumen

Data used in Roadprint: The energy input for bitumen production is 3.98 MJ/kg (3.77E+03 BTU/kg) and 226 g/kg for CO_2 emissions. The inputs/outputs of bitumen production are shown as Table 14. Other sources show that energy input for bitumen production ranges from 2.35-6.0 MJ/kg and that CO_2 output ranges from 171-373 g/kg. ISO 14044 defines feedstock energy as heat that is contained in raw material but not commonly used as an energy source. Bitumen's feedstock energy is estimated to be 40.2 MJ/kg (IPCC, 2006). The total energy of bitumen production is 44.21 MJ/kg (4.19E+04 BTU/kg) if feedstock is taken into consideration.

Table 14 Inputs/outputs of Bitumen Production, per ton (Eurobitume, 2011)

Inputs/outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	-3.77E+06	MJ	-3.98E+03
	Fossil fuels	BTU	-3.61E+06	MJ	-3.81E+03
	Coal	BTU	-2.48E+05	MJ	-2.62E+02
	Natural gas	BTU	-1.14E+06	MJ	-1.21E+03
	Petroleum	BTU	-2.22E+06	MJ	-2.34E+03
Air emissions	CO_2	G	2.26E+05	lb	2.39E+02
	CO	g	1.04E+03	lb	1.10E+00
	NO_x	g	1.14E+03	lb	1.20E+00
	SO_x	g	0.00E+00	lb	0.00E+00
	CH_4	g	7.19E+02	lb	7.59E-01
	$PM_{2.5}$	g	0.00E+00	lb	0.00E+00
	PM_{10}	g	3.00E+02	lb	3.17E-01
	SO_2	g	8.99E+02	lb	9.48E-01
	N_2O	g	0.00E+00	lb	0.00E+00
	VOC	g	4.04E+02	lb	4.26E-01

3.3.2 Cement production

Available data and sources: Cement production data can be found in IVL (Stripple, 2001), VTT (Häkkinen and Mäkelä, 1996), Athena (2006), PCA (2006, 2010).

Selected data source: The PCA cement LCI data is selected. The functional unit is a unit mass of cement manufactured in the US from domestically produced clinkers. The system boundary includes quarry operations, raw meal preparation, pyroprocessing, finish grinding, and all the transportation associated with these activities. Figure 18 shows the system boundary of cement LCI. Data quality score is shown in Table 15.

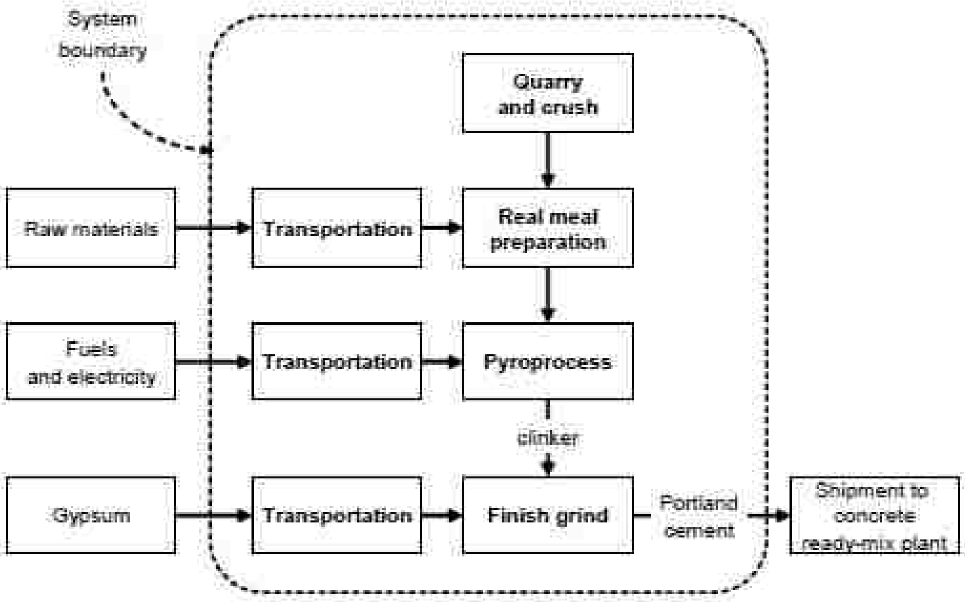


Figure 18 System boundary of cement LCI (Source: PCA, 2006)

Table 15 Cement Production Data Quality Score

Category	Score	Overall Score
Time	5	**3.75**
Geography	3	
Precision, completeness	4	
Consistency and reproducibility	3	

Strength: This is the most up-to-date data source for Portland cement manufacture. The original report was published in 2006, but was updated in 2010. It is specific for U.S. cement production.

Weakness: The data covers only four cement plant processes: wet, long dry, dry with preheater, and dry with preheater and precalciner. The estimates of particulate emissions from sources other than the pyroprocess were developed using AP-42 factors, and may result in conservative estimates.

Data used in Roadprint: The energy input for cement production is 4.34 MJ/kg (4.12E+03 BTU/kg), and the CO_2 emissions are 927 g/kg. The inputs/outputs data for cement production are shown in Table 16. Data from other sources is ranging from 4.8-5.5 MJ/kg and 780-927 g/kg for energy and CO_2 respectively.

Table 16 Inputs/outputs of Cement Production, per ton (PCA, 2006)

Inputs/outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	-4.12E+06	MJ	-4.34E+03
	Fossil fuels	BTU	-3.32E+06	MJ	-3.50E+03
	Coal	BTU	-2.43E+06	MJ	-2.56E+03
	Natural gas	BTU	-1.82E+05	MJ	-1.92E+02
	Petroleum	BTU	-7.14E+05	MJ	-7.53E+02
Air emissions	CO_2	g	9.27E+05	lb	2.04E+03
	CO	g	1.10E+03	lb	2.42E+00
	NO_x	g	2.50E+03	lb	5.51E+00
	SO_x	g	0.00E+00	lb	0.00E+00
	CH_4	g	3.95E+01	lb	8.70E-02
	$PM_{2.5}$	g	0.00E+00	lb	0.00E+00
	PM_{10}	g	2.35E+03	lb	5.18E+00
	SO_2	g	1.66E+03	lb	3.66E+00
	N_2O	g	0.00E+00	lb	0.00E+00
	VOC	g	5.02E+01	lb	1.11E-01

3.3.3 Production of crushed stone, sand and gravel

Available data and sources: Data can be found in IVL (Stripple, 2001), VTT (Häkkinen and Mäkelä, 1996), Athena (2006), PCA (2006, 2010).

Selected data source: The life-cycle inventory of Portland cement concrete (PCA, 2007) also contains data for crushed stone production. However, its emission inventory only covers $PM_{2.5}$ and PM_{10} particulate matter, which is not sufficient for this research. Therefore, only energy input is obtained from that inventory. The additional emission data required are obtained from the report by IVL (Stipple, 2001). Data quality score is shown in Table 17.

Table 17 Crushed Stone, Sand and Gravel Production Data Quality Score

Category	Score	Overall Score
Time	3.5	**3.125**
Geography	2	
Precision, completeness	4	
Consistency and reproducibility	3	

Strength: Both the PCA and IVL reports have a clear system boundary and transparent data sources.

Weakness: Energy and emissions data from different sources might not correspond very well. IVL is specific for Sweden, and cannot represent the situation in the U.S.

Data used in Roadprint: The energy input for crushed stone production is 0.035 MJ/kg (3.05E+01 BTU/kg) and 1.42 g/kg for CO_2 emission. Other data sources range from 0.035-0.12 MJ/kg and 1.42-8.3 g/kg for energy and CO_2, respectively. The energy input for sand/gravel production is 0.023 MJ/kg (1.99E+01 BTU/kg) and 0.073 g/kg for CO_2 emissions. Data from previous studies ranged from 0.006-0.059 MJ/kg and 0.095-1.7 g/kg for energy and CO_2, respectively. The inputs/outputs data are shown in Table 18 and Table 19.

Table 18 Inputs/outputs for Crushed Stone Production, per ton (PCA, 2007)

Inputs/outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	-3.05E+04	MJ	-3.54E+01
	Fossil fuels	BTU	-2.04E+04	MJ	-2.37E+01
	Coal	BTU	-5.77E+02	MJ	-6.70E-01
	Natural gas	BTU	-4.72E+03	MJ	-5.48E+00
	Petroleum	BTU	-1.51E+04	MJ	-1.75E+01
Air emissions	CO_2	g	1.42E+03	lb	3.13E+00
	CO	g	1.49E+00	lb	3.28E-03
	NO_x	g	1.23E-01	lb	2.71E-04
	SO_x	g	0.00E+00	lb	0.00E+00
	CH_4	g	3.82E-03	lb	8.41E-06
	$PM_{2.5}$	g	0.00E+00	lb	0.00E+00
	PM_{10}	g	9.25E-01	lb	2.04E-03
	SO_2	g	7.88E-01	lb	1.74E-03
	N_2O	g	3.60E-02	lb	7.93E-05
	VOC	g	8.90E-01	lb	1.96E-03

Table 19 Inputs/outputs for Sand/gravel Production, per ton (PCA, 2007)

Inputs/Outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	-1.99E+04	MJ	-2.32E+01
	Fossil fuels	BTU	-1.17E+04	MJ	-1.36E+01
	Coal	BTU	0.00E+00	MJ	0.00E+00
	Natural gas	BTU	-2.05E+03	MJ	-2.38E+00
	Petroleum	BTU	-9.68E+03	MJ	-1.12E+01
Air emissions	CO_2	g	7.28E+01	lb	1.60E-01
	CO	g	7.40E-02	lb	1.63E-04
	NO_x	g	5.90E-01	lb	1.30E-03
	SO_x	g	0.00E+00	lb	0.00E+00
	CH_4	g	3.70E-04	lb	8.15E-07
	$PM_{2.5}$	g	0.00E+00	lb	0.00E+00
	PM_{10}	g	2.31E-02	lb	5.09E-05
	SO_2	g	4.70E-02	lb	1.04E-04
	N_2O	g	2.30E-03	lb	5.07E-06
	VOC	g	4.40E-02	lb	9.69E-05

3.3.4 HMA/WMA production

Available data and sources: IVL (Stripple, 2001), VTT (Häkkinen and Mäkelä, 1996), Athena (2006). AP-42 Compilation of Air Pollutant Emission Factors (EPA, 2004) provides only emissions data.

Selected data source: AP-42 is the most appropriate public source of emission outputs for US HMA plants, despite the last update having been almost 10 years ago (EPA, 1995; EPA, 2004). It specifies types of plants and activities that occur in these plants and defines the system boundary well. The report includes no energy input data. Thus, the energy input data were obtained from the study by IVL (Stripple, 2001). Data quality score is shown in Table 20.

Table 20 HMA Production Data Quality Score

Category	Score	Overall Score
Time	3	3
Geography	2	
Precision, completeness	4	
Consistency and reproducibility	3	

Strength: Both the AP-42 and IVL reports have a clear system boundary and transparent data sources.

Weakness: Energy and emissions data from different sources might not correspond very well. IVL is specific for Sweden, and may not fully reflect the processes in the U.S.

Data used in Roadprint: The energy input for HMA plant operation is 0.48 MJ/kg (4.6E+02 BTU/kg) and 15 g/kg for CO_2 emissions. Previous studies reported values ranging from 0.40-0.84 MJ/kg and 22.6-51 g/kg for energy and CO_2, respectively, with Häkkinen and Mäkelä (1996) reporting the higher values, which included bitumen production, aggregate production, and paving machine operations in the HMA production process. There are currently no data available for warm mix asphalt (WMA). Users can enter a "discount ratio," which discounts the energy inputs of HMA to obtain those for WMA mixing. To obtain the emission outputs, it is assumed that all the emissions are proportional to the energy inputs, although this is known to not be the case. Therefore, Roadprint reported emissions resulting from WMA use are likely to be conservative (Chowdhury and Button, 2008; D'Angelo et al., 2008).

Table 21 Inputs/outputs for HMA Production, per ton (Stripple, 2001; AP-42, 2004)

Inputs/outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	-4.60E+05	MJ	-4.85E+02
	Fossil fuels	BTU	-4.26E+05	MJ	-4.49E+02
	Coal	BTU	0.00E+00	MJ	0.00E+00
	Natural gas	BTU	-4.26E+05	MJ	-4.49E+02
	Petroleum	BTU	0.00E+00	MJ	0.00E+00
Air emissions	CO_2	g	1.50E+04	lb	3.30E+01
	CO	g	5.90E+01	lb	1.30E-01
	NO_x	g	1.18E+01	lb	2.60E-02
	SO_x	g	0.00E+00	lb	0.00E+00
	CH_4	g	5.45E+00	lb	1.20E-02
	$PM_{2.5}$	g	4.54E+00	lb	1.00E-02
	PM_{10}	g	1.04E+01	lb	2.30E-02
	SO_2	g	1.54E+00	lb	3.40E-03
	N_2O	g	0.00E+00	lb	0.00E+00
	VOC	g	1.45E+01	lb	3.20E-02

3.3.5 Production of PCC

Available data and sources: PCC production data can be found in IVL (Stripple, 2001), VTT (Häkkinen and Mäkelä, 1996), Athena (2006), PCA (2007).

Selected data source: The data used are obtained from the life-cycle inventory of Portland cement concrete (PCA, 2007). Data quality score is shown in Table 22.

Table 22 PCC Production Data Quality Score

Category	Score	Overall Score
Time	5	3.75
Geography	3	
Precision, completeness	4	
Consistency and reproducibility	3	

Strength: This inventory is the most current US specific data for certain Portland cement concrete. It contains a comprehensive description of the system boundary, and also the sources of the data are transparent compared with other sources.

Weakness: This LCI provides seven specific types of PCC, which might not comprehensively represent all kinds of PCC productions.

Data used in Roadprint: The inventory includes seven types of ready-mixed concrete products. The inputs/outputs for each PCC product are listed in Table 23 through Table 29. Other studies did not covered cement substitutes such as fly ash or blast slag furnace in concrete mixes, hence they reported higher values ranging from 0.635-1.07 MJ/kg and 103-160 g/kg for energy and CO_2, respectively.

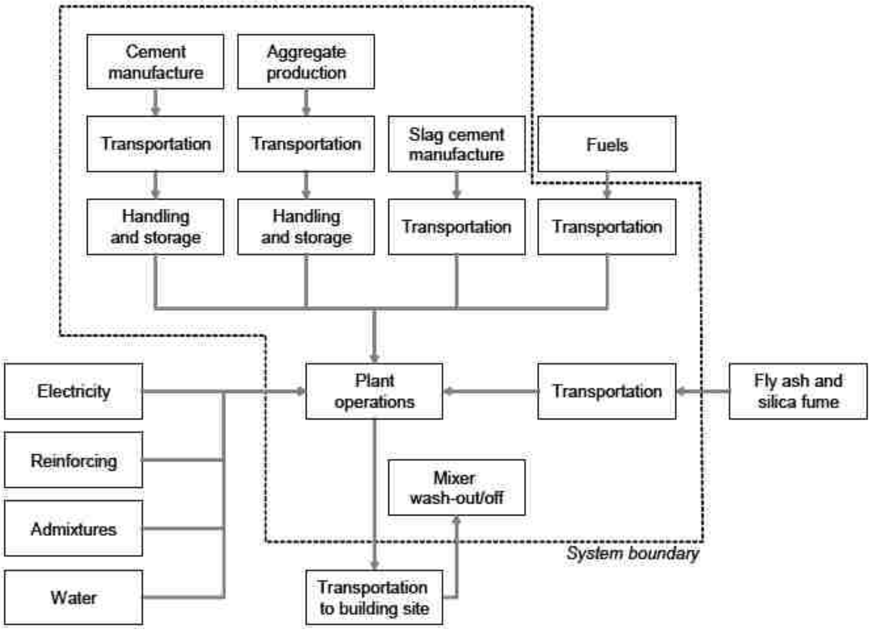


Figure 19 System boundary of Portland cement concrete LCI (Source: PCA, 2007)

Table 23 PCC Production, 5000 psi, per ton (PCA, 2007)

Inputs/outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	-5.83E+05	MJ	-6.14E+02
	Fossil fuels	BTU	-3.29E+05	MJ	-3.47E+02
	Coal	BTU	-2.95E+05	MJ	-3.11E+02
	Natural gas	BTU	-2.33E+04	MJ	-2.45E+01
	Petroleum	BTU	-1.05E+04	MJ	-1.11E+01
Air emissions	CO_2	g	1.18E+05	lb	2.60E+02
	CO	g	1.48E+02	lb	3.25E-01
	NO_x	g	3.12E+02	lb	6.86E-01
	SO_x	g	1.32E+00	lb	2.90E-03
	CH_4	g	4.89E+00	lb	1.08E-02
	$PM_{2.5}$	g	1.80E-02	lb	3.98E-05
	PM_{10}	g	2.17E+02	lb	4.79E-01
	SO_2	g	1.63E+02	lb	3.60E-01
	N_2O	g	0.00E+00	lb	0.00E+00
	VOC	g	7.82E+00	lb	1.72E-02

Table 24 PCC Production, 4000 psi, per ton (PCA, 2007)

Inputs/outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	-4.99E+05	MJ	-5.26E+02
	Fossil fuels	BTU	-2.77E+05	MJ	-2.92E+02
	Coal	BTU	-2.46E+05	MJ	-2.59E+02
	Natural gas	BTU	-2.03E+04	MJ	-2.14E+01
	Petroleum	BTU	-1.07E+04	MJ	-1.13E+01
Air emissions	CO_2	g	9.91E+04	lb	2.18E+02
	CO	g	1.25E+02	lb	2.76E-01
	NO_x	g	2.65E+02	lb	5.83E-01
	SO_x	g	1.30E+00	lb	2.87E-03
	CH_4	g	4.10E+00	lb	9.04E-03
	$PM_{2.5}$	g	1.61E-02	lb	3.56E-05
	PM_{10}	g	2.08E+02	lb	4.59E-01
	SO_2	g	1.36E+02	lb	3.00E-01
	N_2O	g	0.00E+00	lb	0.00E+00
	VOC	g	6.82E+00	lb	1.50E-02

Table 25 PCC Production, 3000 psi, per ton (PCA, 2007)

Inputs/outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	-4.07E+05	MJ	-4.29E+02
	Fossil fuels	BTU	-2.25E+05	MJ	-2.37E+02
	Coal	BTU	-1.97E+05	MJ	-2.07E+02
	Natural gas	BTU	-1.73E+04	MJ	-1.83E+01
	Petroleum	BTU	-1.06E+04	MJ	-1.12E+01
Air emissions	CO_2	g	7.98E+04	lb	1.76E+02
	CO	g	1.03E+02	lb	2.26E-01
	NO_x	g	2.15E+02	lb	4.74E-01
	SO_x	g	1.26E+00	lb	2.78E-03
	CH_4	g	3.32E+00	lb	7.31E-03
	$PM_{2.5}$	g	1.39E-02	lb	3.06E-05
	PM_{10}	g	1.95E+02	lb	4.30E-01
	SO_2	g	1.09E+02	lb	2.40E-01
	N_2O	g	0.00E+00	lb	0.00E+00
	VOC	g	5.76E+00	lb	1.27E-02

Table 26 PCC Production, 3000 psi, 20% fly ash, per ton (PCA, 2007)

Inputs/outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	-3.38E+05	MJ	-3.56E+02
	Fossil fuels	BTU	-1.83E+05	MJ	-1.93E+02
	Coal	BTU	-1.58E+05	MJ	-1.66E+02
	Natural gas	BTU	-1.50E+04	MJ	-1.58E+01
	Petroleum	BTU	-1.05E+04	MJ	-1.11E+01
Air emissions	CO_2	g	6.46E+04	lb	1.42E+02
	CO	g	8.47E+01	lb	1.87E-01
	NO_x	g	1.77E+02	lb	3.91E-01
	SO_x	g	1.26E+00	lb	2.78E-03
	CH_4	g	2.69E+00	lb	5.93E-03
	$PM_{2.5}$	g	1.24E-02	lb	2.73E-05
	PM_{10}	g	1.85E+02	lb	4.06E-01
	SO_2	g	8.92E+01	lb	1.97E-01
	N_2O	g	0.00E+00	lb	0.00E+00
	VOC	g	4.95E+00	lb	1.09E-02

Table 27 PCC Production, 3000 psi, 25% fly ash, per ton (PCA, 2007)

Inputs/outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	-3.20E+05	MJ	-3.37E+02
	Fossil fuels	BTU	-1.73E+05	MJ	-1.82E+02
	Coal	BTU	-1.48E+05	MJ	-1.56E+02
	Natural gas	BTU	-1.44E+04	MJ	-1.51E+01
	Petroleum	BTU	-1.05E+04	MJ	-1.11E+01
Air emissions	CO_2	g	6.08E+04	lb	1.34E+02
	CO	g	8.03E+01	lb	1.77E-01
	NO_x	g	1.68E+02	lb	3.69E-01
	SO_x	g	1.26E+00	lb	2.78E-03
	CH_4	g	2.91E+00	lb	6.42E-03
	$PM_{2.5}$	g	1.20E-02	lb	2.64E-05
	PM_{10}	g	1.82E+02	lb	4.00E-01
	SO_2	g	8.16E+01	lb	1.80E-01
	N_2O	g	0.00E+00	lb	0.00E+00
	VOC	g	4.78E+00	lb	1.05E-02

Table 28 PCC Production, 3000 psi, 35% slag, per ton (PCA, 2007)

Inputs/outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	-3.05E+05	MJ	-3.22E+02
	Fossil fuels	BTU	-1.61E+05	MJ	-1.70E+02
	Coal	BTU	-1.28E+05	MJ	-1.35E+02
	Natural gas	BTU	-2.28E+04	MJ	-2.40E+01
	Petroleum	BTU	-1.05E+04	MJ	-1.10E+01
Air emissions	CO_2	g	5.36E+04	lb	1.18E+02
	CO	g	7.31E+01	lb	1.61E-01
	NO_x	g	1.50E+02	lb	3.30E-01
	SO_x	g	1.26E+00	lb	2.78E-03
	CH_4	g	2.24E+00	lb	4.94E-03
	$PM_{2.5}$	g	1.12E-02	lb	2.47E-05
	PM_{10}	g	1.76E+02	lb	3.89E-01
	SO_2	g	7.76E+01	lb	1.71E-01
	N_2O	g	0.00E+00	lb	0.00E+00
	VOC	g	4.44E+00	lb	9.78E-03

Table 29 PCC Production, 3000 psi, 50% slag, per ton (PCA, 2007)

Inputs/outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	-2.62E+05	MJ	-2.76E+02
	Fossil fuels	BTU	-1.34E+05	MJ	-1.41E+02
	Coal	BTU	-9.83E+04	MJ	-1.04E+02
	Natural gas	BTU	-2.50E+04	MJ	-2.64E+01
	Petroleum	BTU	-1.04E+04	MJ	-1.10E+01
Air emissions	CO_2	g	4.26E+04	lb	9.38E+01
	CO	g	6.05E+01	lb	1.33E-01
	NO_x	g	1.22E+02	lb	2.69E-01
	SO_x	g	1.26E+00	lb	2.78E-03
	CH_4	g	1.80E+00	lb	3.97E-03
	$PM_{2.5}$	g	1.01E-02	lb	2.22E-05
	PM_{10}	g	1.68E+02	lb	3.71E-01
	SO_2	g	6.43E+01	lb	1.42E-01
	N_2O	g	0.00E+00	lb	0.00E+00
	VOC	g	3.86E+00	lb	8.49E-03

3.3.6 Dowel/tie bar Production

Available data and sources: Specific dowel/die bar production data is not available. However, steel production can be found in IVL (Stripple, 2001), VTT (Häkkinen and Mäkelä, 1996), Athena (2006), Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET, Argonne Laboratory, 2006).

Selected data source: Data of "stainless steel production" in GREET 2.7 is used as dowel bar production. The stainless steel is made of 70% recycled steel and 30% virgin steel. Data quality score is shown in Table 30.

Table 30 Dowel Bar Production Data Quality Score

Category	Score	Overall Score
Time	5	**3.5**
Geography	3	
Precision, completeness	3	
Consistency and reproducibility	3	

Strength: GREET 2.7 is specific for the U.S. and it is relatively updated. The system boundary is well documented. The sources and manners of data collection are very transparent.

Weakness: The "stainless steel production" process in GREET does not include the forming, cutting and coating involved in dowel bar production.

Data used in Roadprint: The energy input for steel production is 34.2 MJ/kg (32.4E+04 BTU/kg) and 2100 g/kg for CO_2 emissions. Data from previous studies ranged from 6.1-26.9 MJ/kg and 290-2280 g/kg for energy and CO_2, respectively.

Table 31 Dowel Bar Production, per ton (GREET 2.7, 2006)

Inputs/outputs	Substance	Unit	Value	Unit	Value
Energy	Total energy	BTU	3.24E+07	MJ	3.42E+04
	Fossil fuels	BTU	3.04E+07	MJ	3.20E+04
	Coal	BTU	9.97E+06	MJ	1.05E+04
	Natural gas	BTU	1.97E+07	MJ	2.07E+04
	Petroleum	BTU	7.66E+05	MJ	8.08E+02
Air emissions	CO_2	g	2.10E+06	lb	4.62E+03
	CO	g	6.64E+02	lb	1.46E+00
	NO_x	g	2.46E+03	lb	5.42E+00
	SO_x	g	3.39E+03	lb	7.46E+00
	CH_4	g	4.82E+03	lb	1.06E+01
	$PM_{2.5}$	g	5.75E+02	lb	1.27E+00
	PM_{10}	g	1.95E+03	lb	4.29E+00
	SO_2	g	0.00E+00	lb	0.00E+00
	N_2O	g	3.29E+01	lb	7.24E-02
	VOC	g	2.26E+02	lb	4.97E-01

3.3.7 Aggregate/cement substitute

Five materials are used as aggregate/cement substitute in this research: fly ash, bottom ash, slag, crumb rubber, and cullet. However, currently there is no process data specific for “producing fly ash,” “producing bottom ash,” “producing slag,” and “producing crumb rubber” in publically available sources.

Fly ash, bottom ash, and slag are by-products of particular manufacturing procedures, so the energy inputs and emission outputs can be theoretically accounted for that main product. Consequently, fly these three materials can be viewed as “free products,” which act as a zero process (no energy inputs are required and no emissions are generated for their production) in the LCA calculation. Crumb rubber is also viewed as “free product” simply because the data is lacking. However, crumb rubber is not a by-product, and this process should be updated when data is available.

Data source for cullet production is discussed below:

Available data and sources: the report “Glass Recycling – Life Cycle Carbon Dioxide Emissions” (Enviros, 2003) is the only source for recycled glass.

Selected data source: Data from Enviros (2003) is used in Roadprint. Data quality score is shown in Table 32.

Table 32 Cullet Production Data Quality Score

Category	Score	Overall Score
Time	4	**2.5**
Geography	1	
Precision, completeness	2	
Consistency and reproducibility	3	

Strength: The assumptions, measurement and collecting manners are transparent.

Weakness: No emissions other than CO_2.

Data used in Roadprint: Inputs and outputs data are shown in Table 33.

Table 33 Inputs/outputs for Cullet Production, per ton (Enviros, 2003)

Input/output	Substance	Unit	Value	Unit	Value
Energy	Total Energy	BTU	-3.41E+05	MJ	-3.60E+02
	Fossil Fuels	BTU	0.00E+00	MJ	0.00E+00
	Coal	BTU	0.00E+00	MJ	0.00E+00
	Natural Gas	BTU	0.00E+00	MJ	0.00E+00
	Petroleum	BTU	0.00E+00	MJ	0.00E+00
Emission to Air	CO_2	g	1.80E+04	lb	3.96E+01
	CO	g	0.00E+00	lb	0.00E+00
	NO_x	g	0.00E+00	lb	0.00E+00
	SO_x	g	0.00E+00	lb	0.00E+00
	CH_4	g	0.00E+00	lb	0.00E+00
	$PM_{2.5}$	g	0.00E+00	lb	0.00E+00
	PM_{10}	g	0.00E+00	lb	0.00E+00
	SO_2	g	0.00E+00	lb	0.00E+00
	N_2O	g	0.00E+00	lb	0.00E+00
	VOC	g	0.00E+00	lb	0.00E+00

3.3.8 RAP/RAC production

Available data and sources: The RAP/RAC production can be considered as the combination of surface milling, collection and transportation to storage. VTT (Häkkinen and Mäkelä, 1996) and IVL (Stripple, 2001) included a milling machine, but did not specify the collecting and transporting processes.

Selected data source: HMA milling, PCC crushing, and transport from collection to storage are included in the RAP/RAC production in Roadprint. The weight of milled or crushed material, along with mode/distance of transportation, will be used to determine the inputs/outputs of RAP or RAC. Users can specify milling and transportation activities for the recycled pavement. Energy inputs and emissions outputs can be computed by the equipment and transportation, and they are discussed in Section 3.3.9 and 3.3.10.

There are two options for RAP/RAC production in Roadprint. First, if there is no pavement recycling information available, RAP/RAC will be treated as a free product. Second, the user can view recycling activities in this project as the same activities for collecting RAP/RAC from previous projects. In other words, although RAP/RAC used in the current project were collected from previous projects with unknown details, the assumption is that they were collected by exactly the same practices as those in use on the current project. Therefore those activities are then included in the system boundary of the current project.

3.3.9 Construction equipment

Available data and sources: data for equipment operation can be found in IVL (Stripple, 2001), VTT (Häkkinen and Mäkelä, 1996), Athena (2006), NONROAD (EPA, 2006).

Selected data source: Pavement construction involves plenty of equipment other than trucks. In Roadprint, energy inputs and emission outputs for US equipment can be simulated through the NONROAD model (EPA, 2006) by choosing a machine with a similar engine size (HP). NONROAD was updated to 2008. Data quality score is shown in Table 34.

Table 34 Construction Equipment Data Quality Score

Category	Score	Overall Score
Time	4	4
Geography	5	
Precision, completeness	3	
Consistency and reproducibility	4	

Strength: Users can select equipment type with specific engine size to obtain more precise results. NONROAD has the best geographic accuracy among available sources for US LCAs. The system boundary is well documented. The sources and manners of data collection are transparent.

Weakness: Although it includes abundant types of equipment, it still cannot cover all types of equipment. Therefore limited options on engine sizes might confine users' choices on finding the most appropriate equipment. Some common emissions data are omitted, such as CH_4 and SO_x. Nonroad does not include all construction equipment.

Data used in Roadprint: The LCI of this research includes equipment for embankment, HMA paving, PCC paving, and pavement removal; embankment equipment includes graders, backhoes, excavators, and loaders. HMA paving includes HMA pavers, MTVs, breakdown rollers, and finishing rollers, PCC paving includes PCC spreaders and PCC pavers; pavement removal includes HMA milling machines and PCC crushers. Although the NONROAD model is quite comprehensive, it does not cover all equipment. MTVs, PCC spreaders, and HMA milling machines are not specified. However, these can be simulated as surfacing equipment in this research.

To obtain the inputs/outputs of the equipment, users select an appropriate engine size. Sample results with certain engine sizes are shown in Table 35 to Table 38.

Table 35 Sample Inputs/outputs for Embankment Equipment (Nonroad, 2008)

Inputs/Outputs	Substance	Unit	Grader (175 HP)	Backhoe (100 HP)	Excavator (175HP)	Loader (175HP)
Energy	Total energy	BTU	-5.59E+05	-1.60E+05	-5.46E+05	-5.41E+05
	Fossil fuels	BTU	-5.59E+05	-1.60E+05	-5.46E+05	-5.41E+05
	Coal	BTU	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Natural gas	BTU	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Petroleum	BTU	-5.59E+05	-1.60E+05	-5.46E+05	-5.41E+05
Air emissions	CO_2	g	4.91E+04	1.40E+04	4.80E+04	4.75E+04
	CO	g	1.33E+02	1.54E+02	1.28E+02	1.37E+02
	NO_x	g	3.41E+02	1.27E+02	3.17E+02	3.62E+02
	SO_x	g	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	CH_4	g	5.29E-01	5.61E-01	4.97E-01	5.53E-01
	$PM_{2.5}$	g	2.98E+01	2.28E+01	2.90E+01	2.92E+01
	PM_{10}	g	3.08E+01	2.35E+01	2.99E+01	3.01E+01
	SO_2	g	9.92E+00	1.39E+00	9.70E+00	4.74E+00
	N_2O	g	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	VOC	g	2.78E+01	2.95E+01	2.62E+01	2.91E+01

Table 36 Sample Inputs/outputs for HMA Paving Equipment (Nonroad, 2008)

Inputs/Outputs	Substance	Unit	HMA Paving, Paver (175HP)	Material Transfer Vehicle (300HP)	Breakdown rolling, Roller (175HP)	Finish Rolling, Roller (100HP)
Energy	Total energy	BTU	-5.34E+05	-9.24E+05	-5.25E+05	-3.73E+05
	Fossil fuels	BTU	-5.34E+05	-9.24E+05	-5.25E+05	-3.73E+05
	Coal	BTU	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Natural gas	BTU	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Petroleum	BTU	-5.34E+05	-9.24E+05	-5.25E+05	-3.73E+05
Air emissions	CO_2	g	1.32E+02	8.12E+04	4.61E+04	3.28E+04
	CO	g	4.69E+04	2.35E+02	1.33E+02	2.18E+02
	NO_x	g	3.46E+02	6.68E+02	3.51E+02	2.52E+02
	SO_x	g	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	CH_4	g	0.00E+00	9.65E-01	5.36E-01	4.77E-01
	$PM_{2.5}$	g	2.89E+01	4.45E+01	2.87E+01	3.06E+01
	PM_{10}	g	2.98E+01	4.58E+01	2.96E+01	3.16E+01
	SO_2	g	9.49E+00	1.64E+01	9.32E+00	6.63E+00
	N_2O	g	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	VOC	g	2.80E+01	5.08E+01	2.82E+01	2.51E+01

Table 37 Sample Inputs/outputs for PCC Paving Equipment (Nonroad, 2008)

Inputs/Outputs	Substance	Unit	PCC Placing, Spreader (300HP)	PCC Paving, Paver (600 HP)
Energy	Total energy	BTU	-9.24E+05	-1.54E+06
	Fossil fuels	BTU	-9.24E+05	-1.54E+06
	Coal	BTU	0.00E+00	0.00E+00
	Natural gas	BTU	0.00E+00	0.00E+00
	Petroleum	BTU	-9.24E+05	-1.54E+06
Air emissions	CO_2	g	8.12E+04	1.35E+05
	CO	g	2.35E+02	4.85E+02
	NO_x	g	6.68E+02	1.12E+03
	SO_x	g	0.00E+00	0.00E+00
	CH_4	g	9.65E-01	1.21E+00
	$PM_{2.5}$	g	4.45E+01	6.58E+01
	PM_{10}	g	4.58E+01	6.78E+01
	SO_2	g	1.64E+01	2.73E+01
	N_2O	g	0.00E+00	0.00E+00
	VOC	g	5.08E+01	6.37E+01

Table 38 Sample Inputs/outputs for Pavement Removal Equipment (Nonroad, 2008)

Inputs/Outputs	Substance	Unit	PCC breaking, Guillotine breaker (600HP)	HMA Milling (750 HP)
Energy	Total energy	BTU	-1.21E+06	-2.83E+06
	Fossil fuels	BTU	-1.21E+06	-2.83E+06
	Coal	BTU	0.00E+00	0.00E+00
	Natural gas	BTU	0.00E+00	0.00E+00
	Petroleum	BTU	-1.21E+06	-2.83E+06
Air emissions	CO_2	g	1.06E+05	2.49E+05
	CO	g	3.00E+02	1.44E+03
	NO_x	g	1.02E+03	2.51E+03
	SO_x	g	0.00E+00	0.00E+00
	CH_4	g	1.15E+00	3.26E+00
	$PM_{2.5}$	g	4.64E+01	1.76E+02
	PM_{10}	g	4.78E+01	1.81E+02
	SO_2	g	2.15E+01	5.03E+01
	N_2O	g	0.00E+00	0.00E+00
	VOC	g	6.07E+01	1.72E+02

3.3.10 Transport services

Available data and sources: Data can be found in IVL (Stripple, 2001), VTT (Häkkinen and Mäkelä, 1996), Athena (2006), UWME GREET Data Extraction (Cooper and Lee, 2008).

Selected data source: The data of transport services was obtained from UWME GREET Data Extraction, which extracted and modified data from the original GREET 1.7 (2007). Data quality score is shown in Table 39.

Table 39 Transportation Data Quality Score

Category	Score	Overall Score
Time	5	3.75
Geography	3	
Precision, completeness	4	
Consistency and reproducibility	3	

Strength: This data source is specific to U.S. The system boundary is well documented. The sources and manners of data collection are very transparent. This model specifies fronthaul and backhaul, which are often ignored in other studies.

Weakness: There are three transport modes (barge, train and truck) in GREET, but each mode only has data for specific types of vehicles, which in many cases do not exactly match the vehicles used in the actual project.

Data used in Roadprint: Four transport modes - median-heavy truck, heavy-heavy truck, barge, and locomotive – are covered in this model. The average payload for barge transportation is 1,500 tons, and the fronthaul load is 80%, and the backhaul load is 0%. A diesel train is used for locomotive freight. Medium-heavy trucks have a capacity of 8 tons, the fuel economy is 7.3 mpg, the load for fronthaul is 100%, and the load for backhaul is 0%. The capacity of heavy-heavy truck is 20 tons. The fuel economy is 5 mpg, and the fronthaul load and backhaul load are 100% and 0%, respectively. The inventories for fronthaul/backhaul transportation are shown in Table 40 and Table 41.

Table 40 Inputs/outputs of Fronthaul Transportation (UWME GREET Extraction, 2008)

Inputs/outputs	Substance	Unit	Barge Fronthaul	Rail Fronthaul	Medium Truck Fronthaul	Heavy Truck Fronthaul
Energy	Total energy	BTU	-4.03E+02	-3.70E+02	-2.22E+03	-1.29E+03
	Fossil fuels	BTU	-4.03E+02	-3.70E+02	-2.22E+03	-1.29E+03
	Coal	BTU	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Natural gas	BTU	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Petroleum	BTU	-4.03E+02	-3.70E+02	-2.22E+03	-1.29E+03
Air emissions	CO_2	g	3.42E+01	2.87E+01	1.73E+02	1.01E+02
	CO	g	4.17E-02	7.89E-02	2.57E-01	2.31E-01
	NO_x	g	4.23E-01	5.61E-01	6.57E-01	4.75E-01
	SO_x	g	1.08E-01	2.97E-03	2.19E-02	1.28E-02
	CH_4	g	7.67E-04	1.46E-03	3.40E-03	2.02E-03
	$PM_{2.5}$	g	5.24E-03	1.20E-02	1.62E-02	8.98E-03
	PM_{10}	g	1.05E-02	1.33E-02	1.76E-02	9.76E-03
	SO_2	g	0.00E+00	1.00E+00	2.00E+00	3.00E+00
	N_2O	g	8.06E-04	7.40E-04	6.43E-03	2.59E-03
	VOC	g	1.57E-02	2.74E-02	7.12E-02	4.36E-02

Table 41 Input/output of Backhaul Transportation (UWME GREET Extraction, 2008)

Inputs/outputs	Substance	Unit	Barge Backhaul	Rail Backhaul	Medium Truck Backhaul	Heavy Truck Backhaul
Energy	Total energy	BTU	-1.97E+01	0.00E+00	-1.51E+03	-8.81E+02
	Fossil fuels	BTU	-1.97E+01	0.00E+00	-1.51E+03	-8.81E+02
	Coal	BTU	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Natural gas	BTU	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Petroleum	BTU	-1.97E+01	0.00E+00	-1.51E+03	-8.81E+02
Air emissions	CO_2	g	1.67E+00	0.00E+00	1.17E+02	6.85E+01
	CO	g	2.04E-03	0.00E+00	1.75E-01	1.57E-01
	NO_x	g	2.07E-02	0.00E+00	4.47E-01	3.23E-01
	SO_x	g	5.28E-03	0.00E+00	1.49E-02	8.68E-03
	CH_4	g	3.76E-05	0.00E+00	2.31E-03	2.02E-03
	$PM_{2.5}$	g	2.57E-04	0.00E+00	1.10E-02	6.11E-03
	PM_{10}	g	5.14E-04	0.00E+00	1.19E-02	6.64E-03
	SO_2	g	0.00E+00	1.00E+00	2.00E+00	3.00E+00
	N_2O	g	3.95E-05	0.00E+00	4.37E-03	2.59E-03
	VOC	g	7.67E-04	0.00E+00	4.84E-02	2.96E-02

3.3.11 Energy generation

Available data and sources: Data can be found in IVL (Stripple, 2001), VTT (Häkkinen and Mäkelä, 1996), Athena (2006), GREET 1.7 (Argonne Laboratory, 2008).

Selected data source: GREET 1.7 fuel-cycle analysis is used for the inventory of common energy sources such as electricity, fossil fuel, natural gas and petroleum. Electricity generation data would change based on electricity mix. Users can enter electricity mix in GREET 1.7, and the electricity mix used in Roadprint is from U.S. EIA (2011). Data quality score is shown in Table 42.

Table 42 Energy Generation Data Quality Score

Category	Score	Overall Score
Time	5	**4**
Geography	4	
Precision, completeness	4	
Consistency and reproducibility	3	

Strength: This data source is specific to the U.S and recently updated. The system boundary is well documented. The sources and manners of data collection are transparent.

Weakness: GREET 1.7 only contains common energy sources. Alternative energy, such hydropower and solar power, are not included.

Data used in Roadprint: The inputs/outputs of electricity are influenced by its generation mix.

Table 43 Inputs/outputs of Energy Production (GREET 1.7, 2008)

Inputs/outputs	Substance	Unit	Conventional and LS diesel, at fueling station	Diesel for Nonroad engines	Natural gas as a stationary fuel	Natural gas for electricity generation	Residual oil, at POU	Coal to power plant	Electricity at POU
Energy	Total Energy	BTU	-2.11E+05	-1.82E+05	-7.19E+04	-6.97E+04	-9.81E+04	-2.11E+04	-1.44E+06
	Fossil Fuels	BTU	-2.07E+05	-1.79E+05	-7.15E+04	-6.93E+04	-9.59E+04	-2.10E+04	-5.41E+05
	Coal	BTU	-3.74E+04	-3.22E+04	-2.40E+03	-2.29E+03	-1.68E+04	-6.19E+03	-3.19E+05
	Natural Gas	BTU	-7.10E+04	-6.19E+04	-6.48E+04	-6.27E+04	-3.49E+04	-8.46E+02	-2.22E+05
	Petroleum	BTU	-9.87E+04	-8.46E+04	-4.29E+03	-4.27E+03	-4.42E+04	-1.39E+04	0.00E+00
Air emissions	CO_2	g	1.66E+04	1.45E+04	5.24E+03	5.16E+03	8.36E+03	1.85E+03	4.80E+04
	CO	g	1.35E+01	1.26E+01	7.86E+00	7.63E+00	1.06E+01	2.63E+00	1.55E+01
	NO_x	g	4.55E+01	4.29E+01	2.24E+01	2.18E+01	3.95E+01	1.47E+01	4.55E+01
	SO_x	g	2.26E+01	2.10E+01	1.16E+01	1.15E+01	1.85E+01	7.18E+00	9.34E+01
	CH_4	g	1.05E+02	1.03E+02	1.96E+02	1.75E+02	9.62E+01	1.19E+02	1.36E+00
	$PM_{2.5}$	g	3.91E+00	3.43E+00	5.11E-01	4.93E-01	2.06E+00	4.23E+01	1.90E+00
	PM_{10}	g	1.00E+01	8.67E+00	8.61E-01	8.29E-01	4.87E+00	1.70E+02	3.39E+00
	SO_2	g	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	N_2O	g	2.74E-01	2.41E-01	8.55E-02	8.32E-02	1.48E-01	3.21E-02	1.21E+00
	VOC	g	7.85E+00	7.66E+00	5.76E+00	5.66E+00	6.16E+00	7.66E+00	1.30E+00

Overall data quality score of Roadprint data inventory is shown in Table 44.

Table 44 Data Quality Score of Roadprint Data Inventory (Scoring Mechanism: ISO 2006; Cooper and Kahn, 2012)

Category	Time	Geography	Precision and Completeness	Consistency and Reproducibility	Average	Overall Average
Bitumen	5	1	5	3	3.5	3.51
Cement	5	3	4	3	3.75	
Aggregate	3.5	2	4	3	3.13	
HMA/WMA	3	2	4	3	3	
PCC	5	3	4	3	3.75	
Dowel Bar	5	3	3	3	3.5	
Cullet	4	1	2	3	2.5	
Equipment	4	5	3	4	4	
Transport	5	3	4	3	3.75	
Energy	5	4	4	4	4.25	

3.4 Inventory calculation

Process flow diagrams were one of the most common early tools used by LCA practitioners (Fava et al., 1991; Consoli et al., 1993; Vigon et al., 1993). An example of using a process flow diagram to calculate a life-cycle inventory is provided in Section 2.1.6. However, this method is inefficient when processing huge amounts of unit processes. Therefore, Heijung (1994) proposed the matrix inversion method. The inventory calculation in this research adopts the computational approach proposed by Heijung and Suh (2002), who utilized matrix inversion to compile the LCI using process analysis.

All unit processes in a functional unit can be expressed in matrix. This matrix can be further divided into two matrices, the technology matrix ***A*** and the environmental matrix ***B***. ***A*** is used to describe the economic inflows and outflows through a "certain duration of process operation." Inflows and outflows are defined by negative and positive values, respectively. ***B*** is used to describe environmental effects and resource usage during "certain duration of process operation." The HMA LCA example in Section 2.1.6 is used to illustrate the calculations. To express all of the unit processes by a matrix form, dimensions are defined to represent a kg of aggregate, a kg of bitumen, 1 kg of HMA, a unit of disposed HMA an MJ of electricity, and a kg of CO_2. The flows in Figure 8 can be converted into:

$$\frac{\boldsymbol{A}}{\boldsymbol{B}} = \begin{pmatrix} \text{kg of agg.} \\ \text{kg of bitumen} \\ \text{kg of HMA} \\ \text{HMA disposal} \\ \text{MJ of elec.} \\ \text{kg of CO}_2 \end{pmatrix} = \begin{bmatrix} 1 & 0 & -0.95 & 0 \\ 0 & 1 & -0.05 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 4 & 2 & 0.5 \\ 1 & 4 & 2 & 0.5 \end{bmatrix} = \left[\begin{array}{cccc} 1 & 0 & -0.95 & 0 \\ 0 & 1 & -0.05 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \hline 1 & 4 & 2 & 0.5 \\ 1 & 4 & 2 & 0.5 \\ & & & \end{array}\right]$$

The next step is to set a desired vector ***f***, which represents total demands. In this HMA example, the desired output is 1 kg of HMA production and deposal. Therefore,

$$\boldsymbol{f} = \begin{bmatrix} \text{kg of aggregate} \\ \text{kg of bitumen} \\ \text{kg of HMA} \\ \text{HMA disposal} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$$

Then, a scaling vector ***S***, is introduced to describe the necessary amount of ***A***, and then the desired demand can be shown as:

$$f = AS.$$

Therefore scaling vector can then be obtained by matrix inversion:

$$S = A^{-1}f = \begin{bmatrix} 1 & 0 & 0.95 & 0 \\ 0 & 1 & 0.05 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0.95 \\ 0.05 \\ 1 \\ 1 \end{bmatrix}$$

Consequently, ***g***, total environmental effects, and resources usage for producing total demand ***f*** can be obtained by multiplying the environmental matrix ***B*** to the scaling vector ***S***:

$$g = BS; \text{ and } S = A^{-1}f, \quad \text{therefore,}$$

$$g = BA^{-1}f = \begin{bmatrix} 1 & 4 & 2 & 0.5 \\ 1 & 4 & 2 & 0.5 \end{bmatrix} \begin{bmatrix} 0.95 \\ 0.05 \\ 1 \\ 1 \end{bmatrix} = \begin{pmatrix} 3.65 \text{ kg} & CO_2 \\ 3.65 \text{ MJ} & \text{Elec.} \end{pmatrix}$$

3.5 Life-cycle impact assessment (LCIA)

The goal of this tool is to obtain environmental burdens of a specific pavement project. Energy consumption, electricity, fossil fuel, crude oil, and coal are the selected inputs of this model. The air emissions CO_2, NO_x, CO, SO_2, PM_{10}, CH_4, N_2O, and VOC are selected according to the discussion in Section 2.3.3. These outputs can be classified according to their potential impacts on the environment, human health, or resources.

The US EPA has suggested that impact assessment may follow the application of the Framework for Responsible Environmental Decision (FRED) or the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) methods (EPA 2000, 2003). There are eight categories for FRED and TRACI, as shown in Table 45 (FRED, 2000; TRACI, 2003).

Based on data consistency and availability, impact categories used in this research include global warming, acidification, eutrophication (above from FRED), photochemical smog, and human toxicity (TRACI).

Table 45 Impact Categories in FRED and TRACI (*Source*: FRED, 2000; TRACI, 2003)

	FRED	**TRACI**
Impact Categories	Global warming	Global warming
	Stratospheric ozone depletion	Ozone depletion
	Acidification	Acidification
	Photochemical smog	Photochemical smog
	Eutrophication	Eutrophication
	Human toxicity	Human health
	Ecological toxicity	Ecotoxcity
	Resource depletion	Resource depletion

3.6 Productivity simulation (see Appendix A for details)

Pavement contractors would want to know the potential paving productivity with their available resources (equipment, truck fleet, etc.), in order to optimize the working efficiency, or to avoid project delay. The productivity of a paving project can be obtained as a by-product of pavement LCAs.

There are six necessary elements to calculate pavement productivity. The hauling distance and the amount of equipment (spreaders/pavers/MTVs/rollers) are existing inputs in the LCA calculation. Users are required to enter plant supply rates, the capacity of trucks, the waiting times at plants/sites, and the average travel speed to calculate the paving productivity and the required number of trucks. If plant supply rate is higher than paving productivity, it means paving activity will not be interrupted by waiting for mixture, and the contractors can either boost the paving speed or lower the plant supply rate. Contrarily, if plant supply rates are lower than paving productivity, contractors have to either raise the supply rate or slow down the paving activity.

3.7 Parameter Uncertainty and probabilistic analysis

In Roadprint, probabilistic analysis is conducted by using Monte Carlo simulation. To generate random number, probability density function (PDF) must be determined before implementing the simulation. The Normal distribution is used as the PDF in Roadprint for Monte Carlo simulation. Mean and standard deviation of the distribution are required to generate a set of random numbers. The amount of iteration is ten thousand runs for one simulation.

Roadprint can analyze parameter uncertainty of “material production,” “transportation,” “construction equipment,” and “paving productivity.” The probabilistic analysis in Roadprint is not fully developed yet. Appropriate distributions for different inputs need to be further determined. Sensitivity and correlations coefficient of variables also need to be further developed. Despite the limitations, the outputs can show the variability in the results, which can help in better interpreting LCIA results.

WA-PCC, a test case described in Section 4.1.1, is used as an example to describe the probabilistic analysis feature in Roadprint. Detail information of WA-PCC can be found in Chapter 4 and Appendix C. The following section describes the inputs and data used in probabilistic analysis for materials production, equipment operations, transportation and paving productivity.

3.7.1 Material production

According to the result that will be shown later in Section 4.1.2, the material production phase was the most significant contributor to pavement LCA results.

Table 46 summarizes data of major materials from reviewed literature. Highlighted cells are used as Roadprint inventory in accordance with the descriptions in Section 3.3. The standard deviations (σ_{all}) of these values are listed in this table. The standard deviations can express the variety of data. Roadprint-selected data and σ_{all} are used as mean and standard to generate random number for Monte Carlo simulation. Roadprint-selected data is used instead of the means (μ_{all}) because it has the best data quality comparing with other data sources.

Confidence interval can provide more information for users to understand the reliability of the results. In Roadprint, 90% confidence interval of probabilistic analysis is showed, as in Table 47, Figure 20 and Figure 21. Users can change the displayed confidence interval if they wish.

Table 46 Data Comparison of Major Materials

Data Source	Energy (MJ/kg)							CO2 (g/kg)					
	Cement	Bitumen	Crushed stone	PCC	HMA	Steel	HMA with feedstock	Cement	Bitumen	Crushed stone	PCC	HMA	Steel
VTT (Häkkinen and Mäkelä, 1996)	5.4	6.0	0.05	1.07	0.84	6.1	3.5	780.0	330.0	2.0	160.0	51.0	290.0
Athena (2006)	5.2	5.8	0.10	0.70	0.40	11.3	2.9	908.2	373.8	8.0	103.0	26.2	565.0
IVL (Stripple, 2001)	5.5	3.7	0.07	0.64	0.48	25.2	3.6	806.0	173.0	1.4	123.4	22.6	2220.0
PaLATE v2.2 (Greenroads 2010)	5.5	2.3	0.12	-	-	26.9	-	851.3	171.0	8.3	-	-	2280.0
EIOLCA	5.5	2.3	0.02	1.34	1.33	27.0	-	851.3	171.0	8.3	156.6	96.9	2279.5
OASIS (González and García, 2009)	3.6	2.1	0.14	-	-	8.5	-	794.0	307.0	7.6	-	-	684.6
PCA (2007)	4.8	-	0.04	0.61	-	-	-	927.0	-	-	117.8	-	-
Eurobitume (2011)	-	4.7	-	-	-	-	-	-	233.0	-	-	-	-
GREET 2.7 (Argone Lab, 2007)	-	-	-	-	-	34.2	-	-	-	-	-	-	2100.0
PE-2 (Mukherjee, 2012)	-	-	-	-	-	-	-	841.0	157.0	6.2	102.6	11.1	354.0
Roadprint	4.8	4.7	0.04	0.61	0.48	34.2	3.3	927.0	233.0	1.4	117.8	15.0	2100.0
Mean	5.0	4.0	0.07	0.83	0.71	21.7	3.3	854.0	238.8	5.4	125.9	37.1	1430.3
Median	5.3	4.2	0.06	0.67	0.48	26.0	3.4	851.3	233.0	6.9	117.8	24.4	2100.0
Standard deviation	0.6	1.5	0.04	0.28	0.35	10.6	0.3	52.9	75.6	3.0	21.7	29.6	864.6

Table 47 Probabilistic Analysis of Material Production Phases, WA-PCC

	Material	
	Energy (MJ)	GHG (Mg)
Mean	8142.68	490.92
Median	8149.29	491.86
Standard deviation	1217.21	113.24
Max	12939.20	915.05
Min	3490.82	51.70
90% interval-Low	6140.56	304.65
90% interval-high	10144.81	677.18

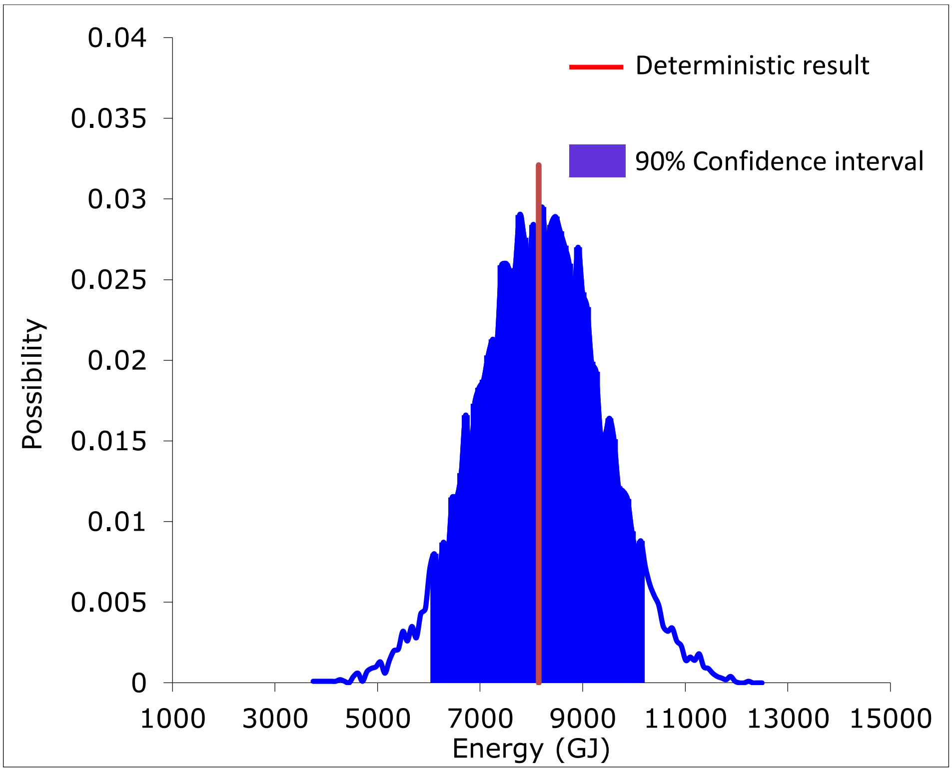


Figure 20 Probability density of energy from materials (GJ), WA-PCC

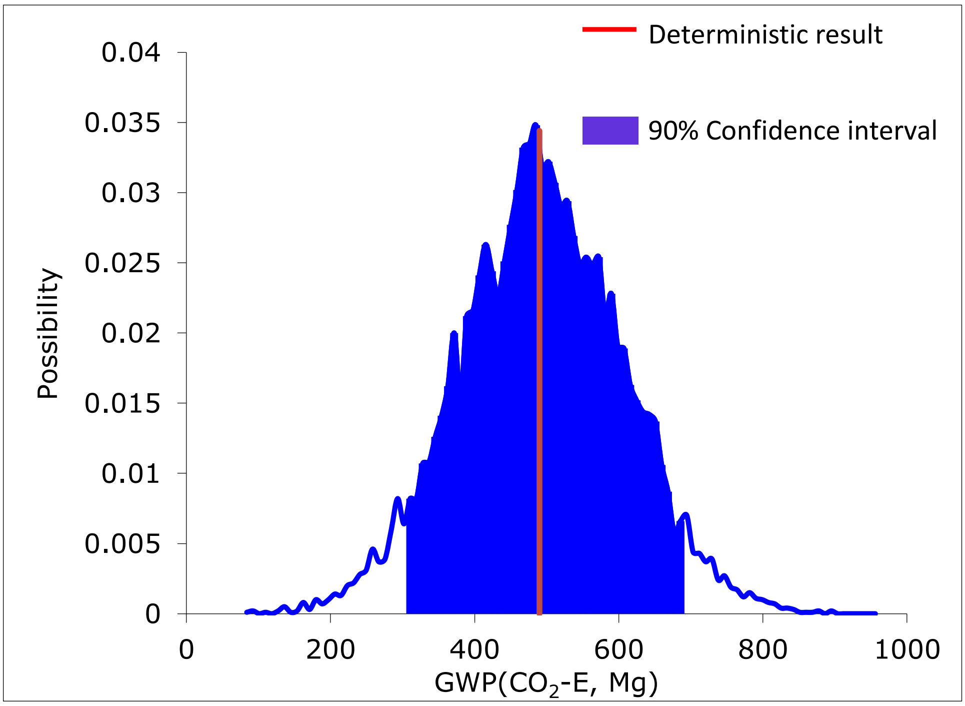


Figure 21 Probability density of GWP from materials (Mg), WA-PCC

3.7.2 Equipment operation

To run probabilistic analysis on equipment operating hours, user-entered working time and efficiency factor are used as μ, and an assumed standard deviation of 0.05μ is used for the normal distribution function. Results are shown in Table 48 and Figure 22 and Figure 23.

Table 48 Probabilistic Analysis of Equipment Operation, WA-PCC

	Equipment	
	Energy (MJ)	GHG (Mg)
μ	379.14	30.51
Median	379.16	30.51
σ	4.70	0.38
Max	397.99	31.95
Min	361.31	29.03
90% interval-Low	371.41	29.87
90% interval-high	386.87	31.14

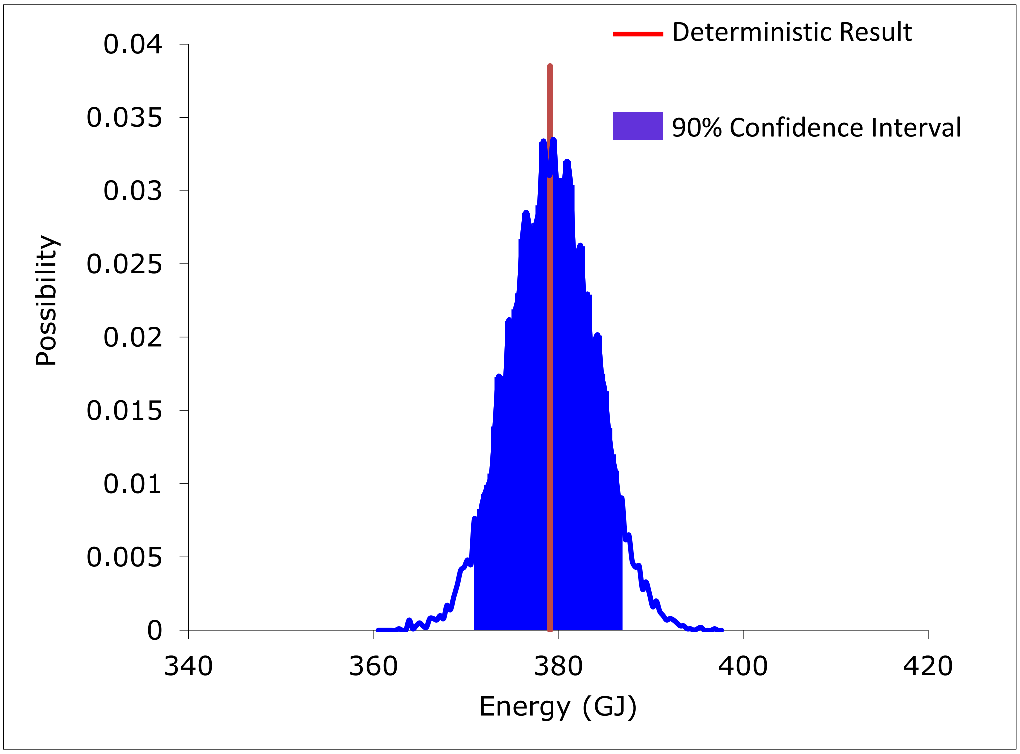


Figure 22 Probability density of energy from equipment operation, WA-PCC

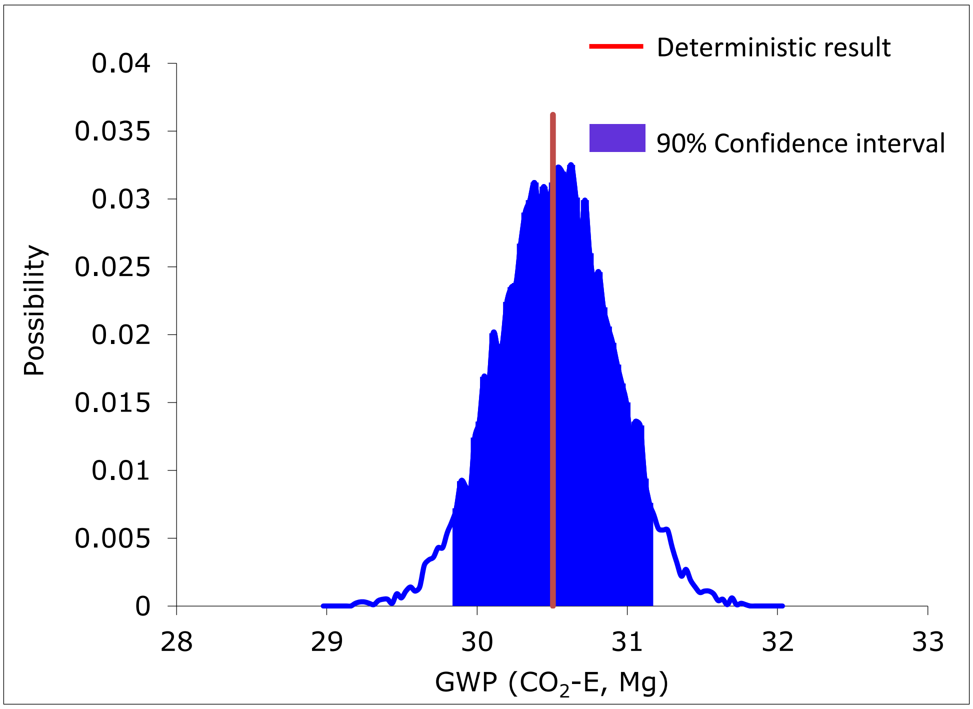


Figure 23 Probability density of GWP from equipment operation, WA-PCC

3.7.3 Transportation

To evaluate the uncertainty of transport distance, user-entered distance is used as mean μ, and standard deviation is assumed 0.05μ for all entered distances. Results are shown in Table 49, Figure 24 and Figure 25.

Table 49 Probabilistic Analysis of Transport Distance, WA-PCC

	Transportation	
	Energy (MJ)	GHG (Mg)
μ	799.88	61.14
Median	799.86	61.13
σ	11.69	0.87
Max	843.41	64.38
Min	754.78	57.78
90% interval-Low	780.65	59.71
90% interval-high	819.11	62.57

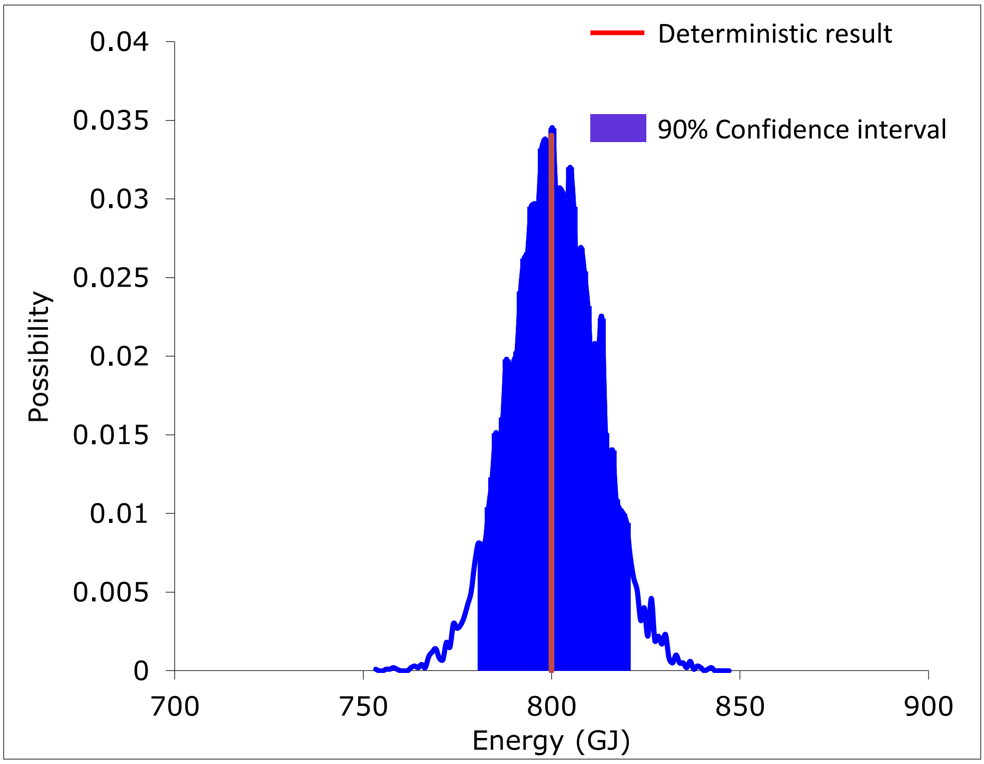


Figure 24 Probability density of energy from transportation, WA-PCC

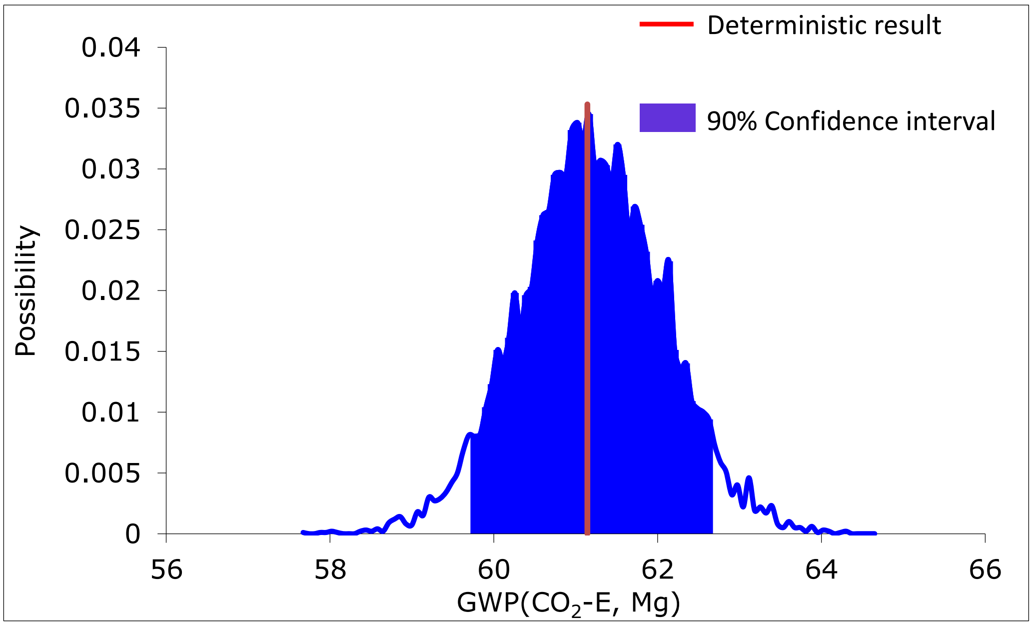


Figure 25 Probability density of GWP from transportation, WA-PCC

3.7.4 Paving productivity

Paving productivity, like equipment operating hours, is related to equipment capacity and efficiency. Therefore it is uncertain due to equipment parameters. The probabilistic analysis can apply the same logic described in the equipment probabilistic analysis. Entered working time/efficiency factors were used as mean μ, and standard deviation of 0.05μ is used for the normal distribution function. Probabilistic analysis of paving productivity is shown in Table 50, Figure 26 and Figure 27.

Table 50 Probabilistic Analysis of Paving Productivity (ton/hr), WA-PCC

	HMA	PCC
Mean	58.15	79.40
Median	58.16	79.45
Standard deviation	2.90	4.02
Max	68.89	95.64
Min	47.06	64.88
90% interval-Low	53.38	72.78
90% interval-high	62.92	86.02

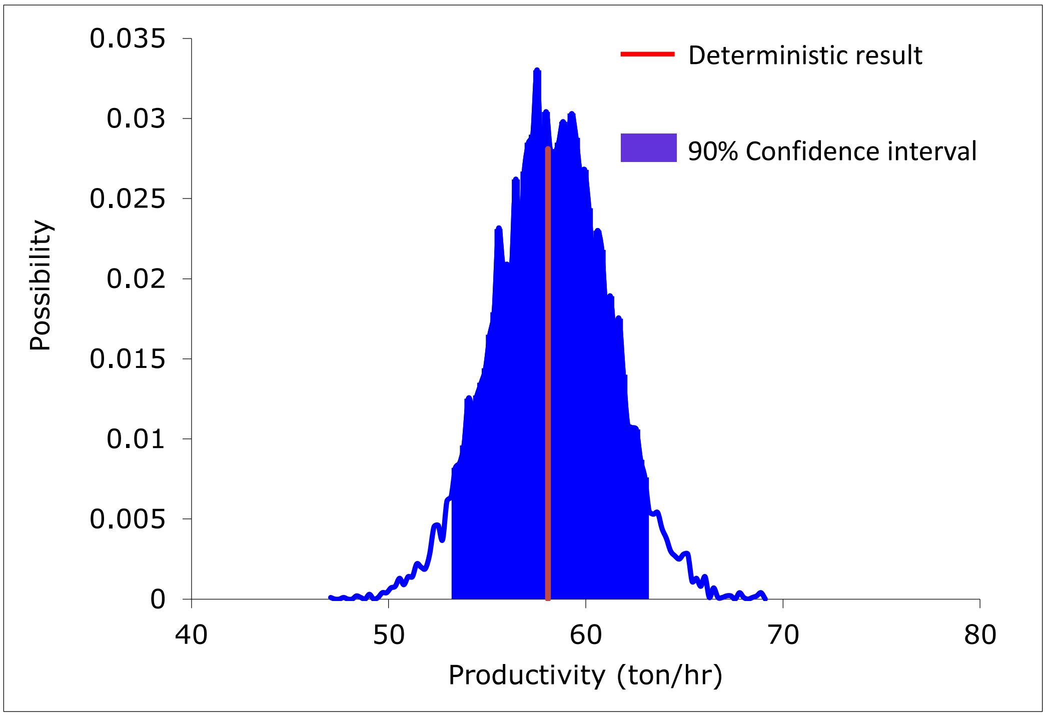


Figure 26 Probability density of HMA initial paving productivity, WA-PCC

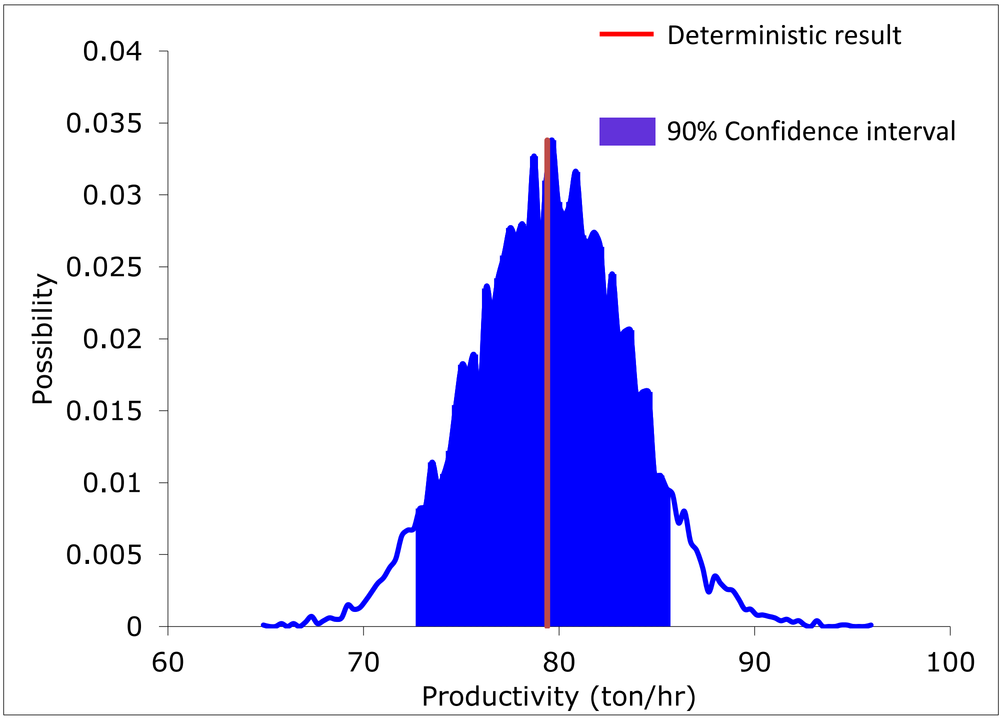


Figure 27 Probability density of PCC initial paving productivity, WA-PCC

3.7.5 Observation on probabilistic analysis

For the built-in data of major materials, the standard deviation was calculated according to reference data, and the relatively high variation among the reference data was the reason for the big range of the results in this phases.

For user-entered parameters, an assumed standard deviation 0.05μ was used, and it only made slight variation of the result. However, the assumed value should be replaced when users possess better information.

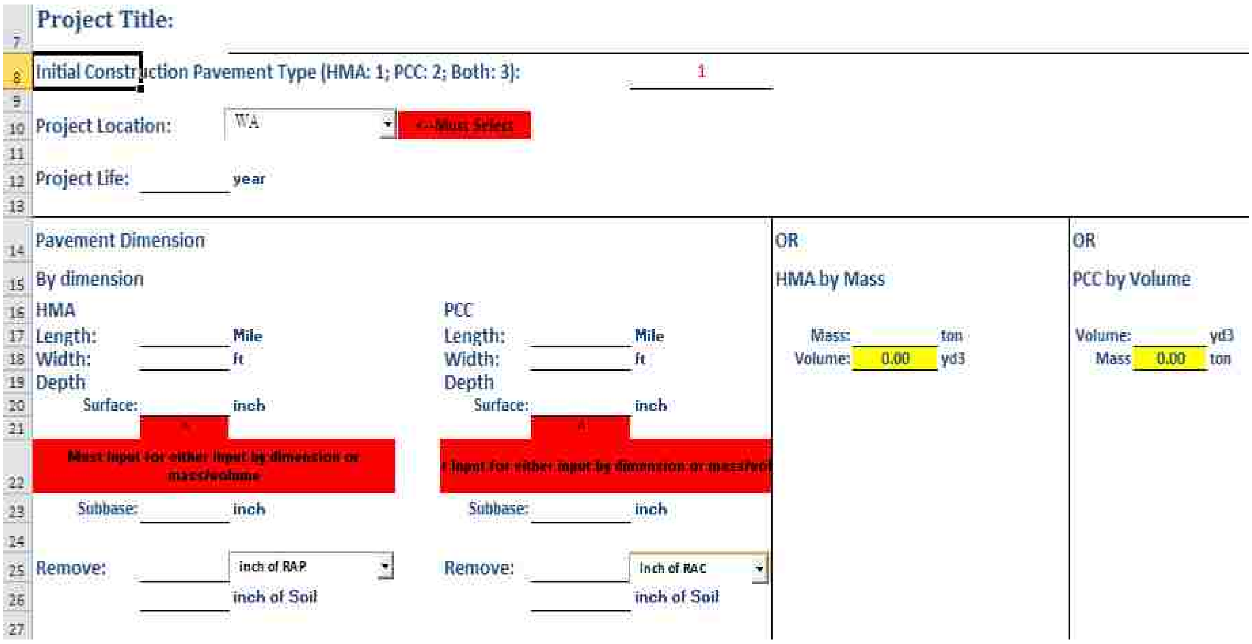
When considering the whole lifecycle together, uncertainty in material production was the most influential: even a small variation in this phase could possibly have higher impacts than the impacts resulted from big variation in equipment and transportation phases.

3.8 LCA tool overview

Roadprint is built with Microsoft Excel 2010. The Excel workbook contains four types of worksheets: 1) the project-specific input, 2) supportive data, 3) LCA calculation, and 4) results. Users enter the required data in the “project-specific input” worksheets. There are three “project-specific input” worksheets to be entered by users:

1) Project information (Figure 28)

In this worksheet, users have to specify basic project information. They select a location from the list and then input the pavement amount by dimension, mass or volume, based on the available information. If the existing surface will be removed, enter the thickness removed, in inches, and specify the type of surface removed. Enter the maintenance type (often referred to in the pavement industry as "rehabilitation") and the number of occurrences over the analysis period. Based on the available data, enter this information by dimension, mass, or volume.



Project Title:

Initial Construction Pavement Type (HMA: 1; PCC: 2; Both: 3): 1

Project Location: WA <--Must Select

Project Life: ____ year

Pavement Dimension

By dimension

HMA
Length: ____ Mile
Width: ____ ft
Depth
Surface: ____ inch
Must input for either input by dimension or mass/volume
Subbase: ____ inch
Remove: ____ inch of RAP
____ inch of Soil

PCC
Length: ____ Mile
Width: ____ ft
Depth
Surface: ____ inch
Input for either input by dimension or mass/vol
Subbase: ____ inch
Remove: ____ Inch of RAC
____ inch of Soil

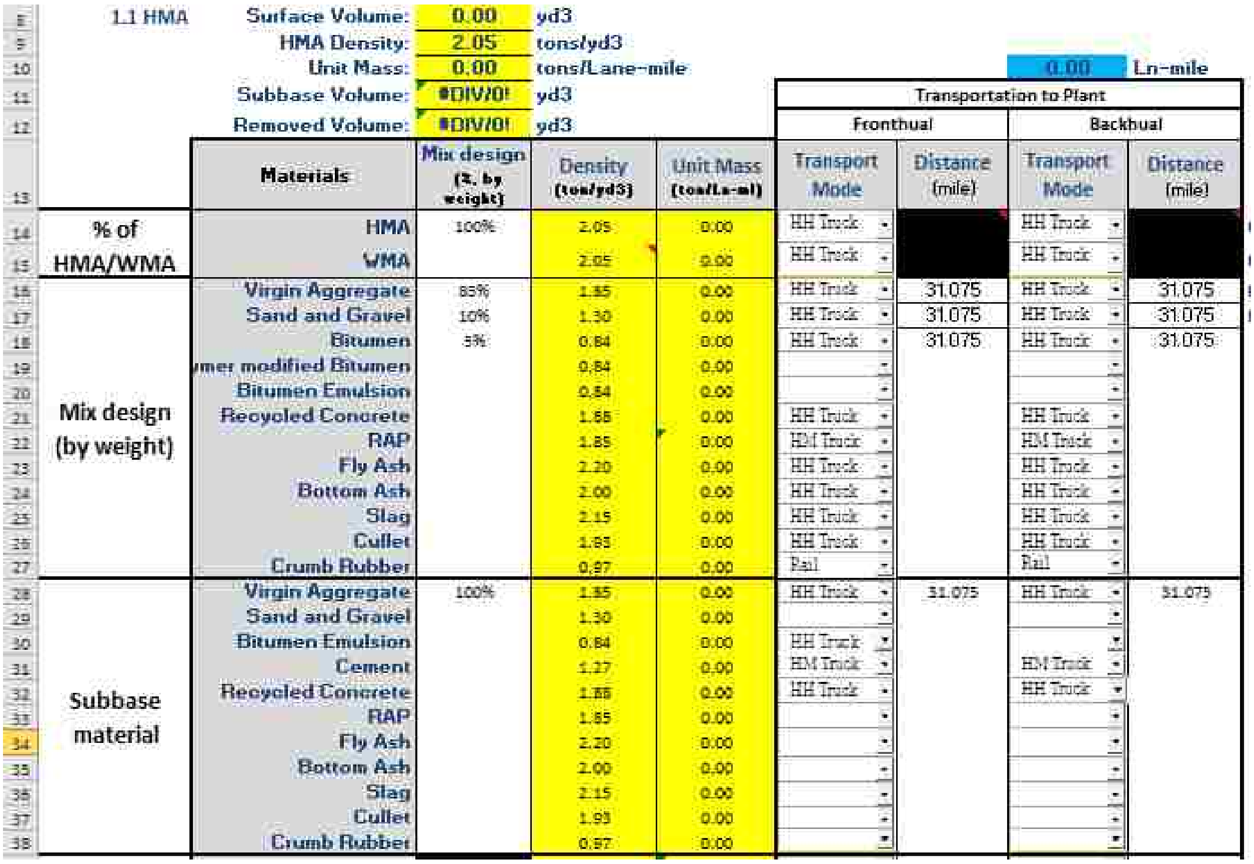
OR
HMA by Mass
Mass: ____ ton
Volume: 0.00 yd3

OR
PCC by Volume
Volume: ____ yd3
Mass 0.00 ton

Figure 28 Screenshot of partial "Project Info" worksheet

2) Material inputs (Figure 29)

In this worksheet, users have to enter the usage of HMA/WMA and PCC. If used, users can specify the WMA energy discount ratio. Users can specify the percentage by weight for the mix design of HMA. Quantity of each constituent is then calculated by the total amount of HMA and the mix design. In addition, users can specify which material is used for the sub-base and the corresponding percentage. There are seven types of ready mix concrete to choose from. Users can enter the information about the steel bar used in the PCC pavement. Last, users select a transport mode and specify fronthaul/backhaul transportation for each material.



1.1 HMA

Surface Volume: 0.00 yd3
HMA Density: 2.05 tons/yd3
Unit Mass: 0.00 tons/Lane-mile
Subbase Volume: #DIV/0! yd3
Removed Volume: #DIV/0! yd3

0.00 Ln-mile

					Transportation to Plant			
					Fronthual		Backhual	
	Materials	Mix design (%, by weight)	Density (ton/yd3)	Unit Mass (ton/Ln-ml)	Transport Mode	Distance (mile)	Transport Mode	Distance (mile)
% of HMA/WMA	HMA	100%	2.05	0.00	HH Truck		HH Truck	
	WMA		2.05	0.00	HH Truck		HH Truck	
Mix design (by weight)	Virgin Aggregate	85%	1.85	0.00	HH Truck	31.075	HH Truck	31.075
	Sand and Gravel	10%	1.30	0.00	HH Truck	31.075	HH Truck	31.075
	Bitumen	5%	0.84	0.00	HH Truck	31.075	HH Truck	31.075
	ymer modified Bitumen		0.84	0.00				
	Bitumen Emulsion		0.84	0.00				
	Recycled Concrete		1.88	0.00	HH Truck		HH Truck	
	RAP		1.85	0.00	HM Truck		HM Truck	
	Fly Ash		2.20	0.00	HH Truck		HH Truck	
	Bottom Ash		2.00	0.00	HH Truck		HH Truck	
	Slag		2.15	0.00	HH Truck		HH Truck	
	Cullet		1.93	0.00	HH Truck		HH Truck	
	Crumb Rubber		0.97	0.00	Rail		Rail	
Subbase material	Virgin Aggregate	100%	1.85	0.00	HH Truck	31.075	HH Truck	31.075
	Sand and Gravel		1.30	0.00				
	Bitumen Emulsion		0.84	0.00	HH Truck			
	Cement		1.27	0.00	HM Truck		HM Truck	
	Recycled Concrete		1.88	0.00	HH Truck		HH Truck	
	RAP		1.85	0.00				
	Fly Ash		2.20	0.00				
	Bottom Ash		2.00	0.00				
	Slag		2.15	0.00				
	Cullet		1.93	0.00				
	Crumb Rubber		0.97	0.00				

Figure 29 Screenshot of partial “Material Inputs” worksheet

3) Equipment inputs(Figure 30)

In this worksheet, users enter the equipment parameters to calculate equipment operating hours. These parameters include:

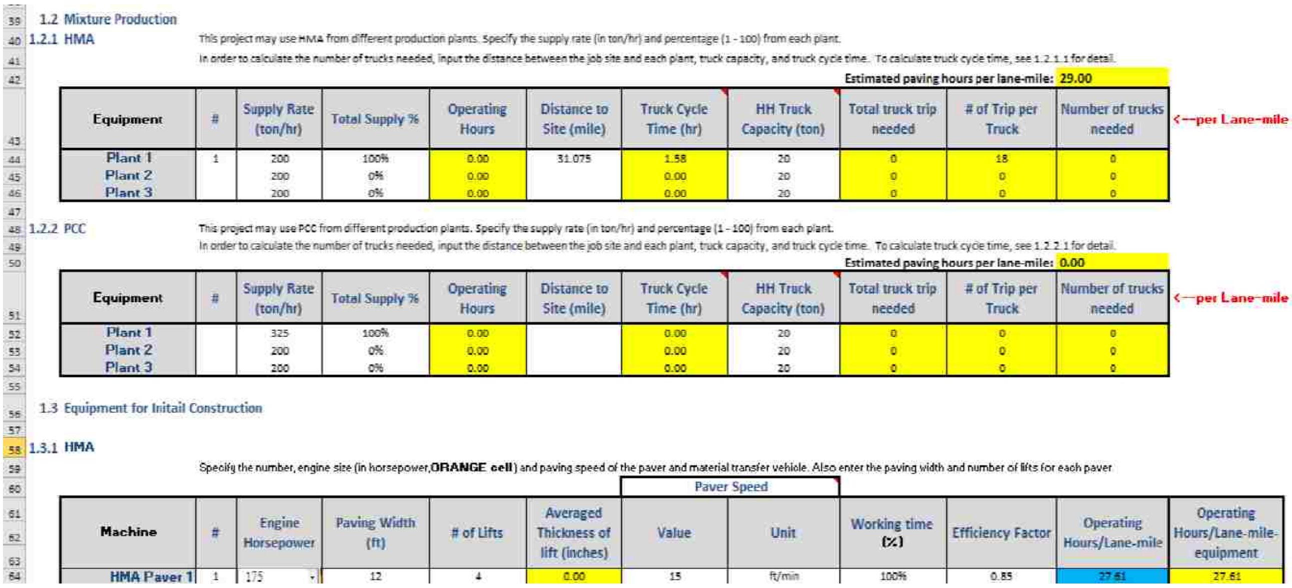
(a) Capacity and efficiency. Capacity of equipment could be in form of speed (ft/min), area (ft^2/hr) or production rate (ton/hr). These indexes are the expected performance of equipment. However, equipment might (or might not) be operated at its 100% capacity. Therefore, users can enter efficiency factor to better describe equipment operation. Operating hours of each equipment is calculated by the equation:

$$\text{Operating hours} = \frac{\text{Total pavement area/volume/mass}}{\text{Equipment capacity } \times \text{Efficiency}}$$

(b) Equipment dimension. Moldboard width of grader, drum width of roller, and paver width are required equipment dimensions. Capacities of grader, roller and paver are expressed in speed, thus width are necessary to convert the capacity from speed to area, to calculate operating hours of these three equipment.

(c) Working time. There are equipment not directly involve in the primary paving train, such as secondary paver/roller, backhoe, loader, and excavator. These equipment may only be used for miscellaneous work and not operate during the entire paving time. Therefore, working time (in %) is introduced to describe the operations of non-primary equipment.

(d) Engine size. Users can select the engine horsepower for all equipment used. This allows Raodprint to more precisely address environmental impacts caused by equipment operations.



1.2 Mixture Production

1.2.1 HMA

This project may use HMA from different production plants. Specify the supply rate (in ton/hr) and percentage (1 - 100) from each plant.

In order to calculate the number of trucks needed, input the distance between the job site and each plant, truck capacity, and truck cycle time. To calculate truck cycle time, see 1.2.1.1 for detail.

Estimated paving hours per lane-mile: 29.00

Equipment	#	Supply Rate (ton/hr)	Total Supply %	Operating Hours	Distance to Site (mile)	Truck Cycle Time (hr)	HH Truck Capacity (ton)	Total truck trip needed	# of Trip per Truck	Number of trucks needed
Plant 1	1	200	100%	0.00	31.075	1.58	20	0	18	0
Plant 2		200	0%	0.00		0.00	20	0	0	0
Plant 3		200	0%	0.00		0.00	20	0	0	0

<--per Lane-mile

1.2.2 PCC

This project may use PCC from different production plants. Specify the supply rate (in ton/hr) and percentage (1 - 100) from each plant.

In order to calculate the number of trucks needed, input the distance between the job site and each plant, truck capacity, and truck cycle time. To calculate truck cycle time, see 1.2.2.1 for detail.

Estimated paving hours per lane-mile: 0.00

Equipment	#	Supply Rate (ton/hr)	Total Supply %	Operating Hours	Distance to Site (mile)	Truck Cycle Time (hr)	HH Truck Capacity (ton)	Total truck trip needed	# of Trip per Truck	Number of trucks needed
Plant 1		325	100%	0.00		0.00	20	0	0	0
Plant 2		200	0%	0.00		0.00	20	0	0	0
Plant 3		200	0%	0.00		0.00	20	0	0	0

<--per Lane-mile

1.3 Equipment for Initail Construction

1.3.1 HMA

Specify the number, engine size (in horsepower,**ORANGE cell**) and paving speed of the paver and material transfer vehicle. Also enter the paving width and number of lifts for each paver

Machine	#	Engine Horsepower	Paving Width (ft)	# of Lifts	Averaged Thickness of lift (inches)	Paver Speed		Working time (%)	Efficiency Factor	Operating Hours/Lane-mile	Operating Hours/Lane-mile-equipment
						Value	Unit				
HMA Paver 1	1	175	12	4	0.00	15	ft/min	100%	0.85	27.61	27.61

Figure 30 Screenshot of partial "Equipment Inputs" worksheet

Supportive data includes "PCC production," "Electricity," "Nonroad," "Conversion," "Transportation," and "Density". These worksheets contain general and supplementary data used for implementing pavement LCA.

LCA calculation worksheets implement the matrix inversion and probabilistic simulations.

The LCA results will be presented in “Results in Chart” and “Results in Table” worksheets. Outputs include energy consumption (GJ), global warming potential (GWP, CO_2 Mg-E), and other impacts: acidification (Kg SO_2), photochemical smog (Kg NO_x), eutrophication (Kg PO_4), and human-health criteria air (milli - DALYs/Kg). For a better understanding of the materials production phase, Roadprint can deconstruct this phase into constituent materials. Up-stream material productions are usually controlled by the material extractors/suppliers/manufacturers. Contractors can decide, however, the distances that the materials will be transported. Roadprint can also deconstruct the energy/GWP of transportation for into constituent materials. Figure 31 is the screenshot of part of the “Result in Chart” worksheet. The result of uncertainty analysis will be presented in “Probabilistic Analysis” worksheet, as shown in Figure 32.

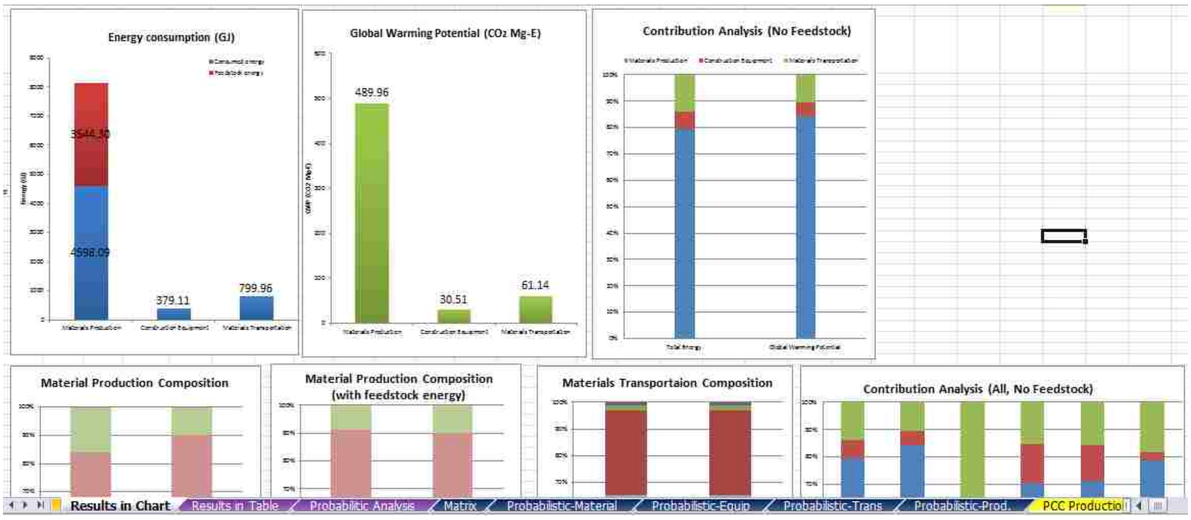


Figure 31 Screenshot of partial “Results in Chart” worksheet

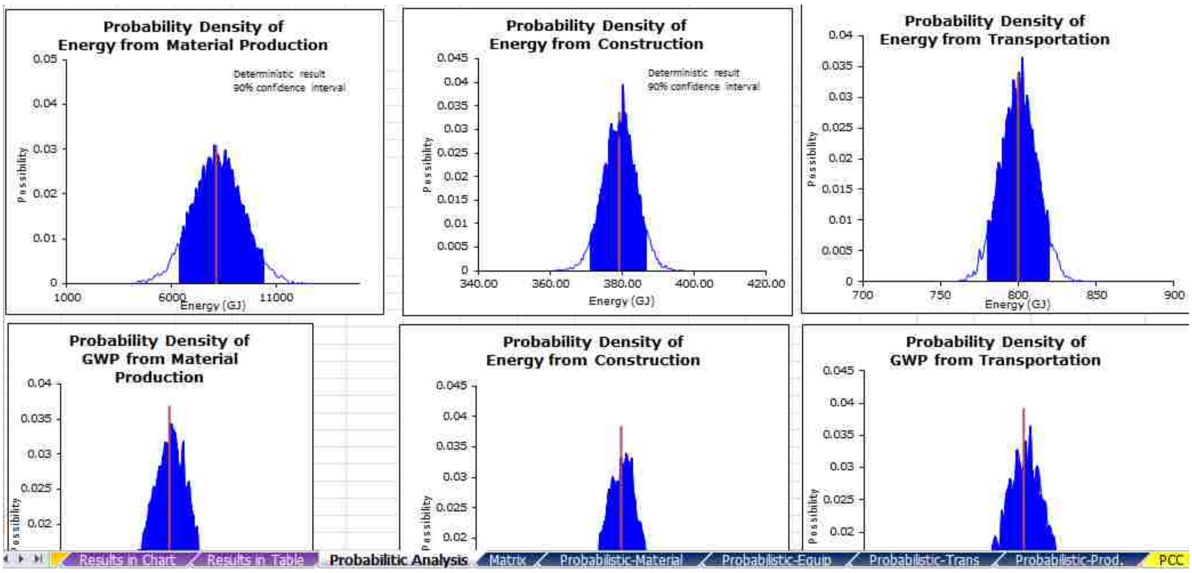


Figure 32 Screenshot of partial “Probabilistic Analysis” worksheet

Chapter 4. Roadprint Assessment

At the end of model/tool development, there is usually a “calibration” or “validation” process. This is typically done by comparing modeled outputs with directly observed data. However, LCA system boundaries may vary, and currently there is no comparative data set or actual observations with a similar system boundary to Roadprint. Collecting data for validation is beyond the scope of this dissertation but could be accomplished by future work. As a reasonable proxy for validation, this Chapter describes three procedures to test Roadprint and compares the generated results with previously reported pavement LCA results (see Chapter 2) and other publically available LCA tools.

First, two WSDOT standard pavement designs were evaluated using Roadprint. The results were compared with results from previous studies to determine how these relate to those of Roadprint. Second, Roadprint was used to evaluate six standard pavement designs and its results were compared with those obtained with three other publically available pavement LCA tools. Finally, this research utilized parameters from three projects, which represent different types of pavement construction, to further assess how Roadprint’s results differ between three very different paving projects using, to the extent possible, actual project data.

4.1 Two WSDOT standard pavement designs

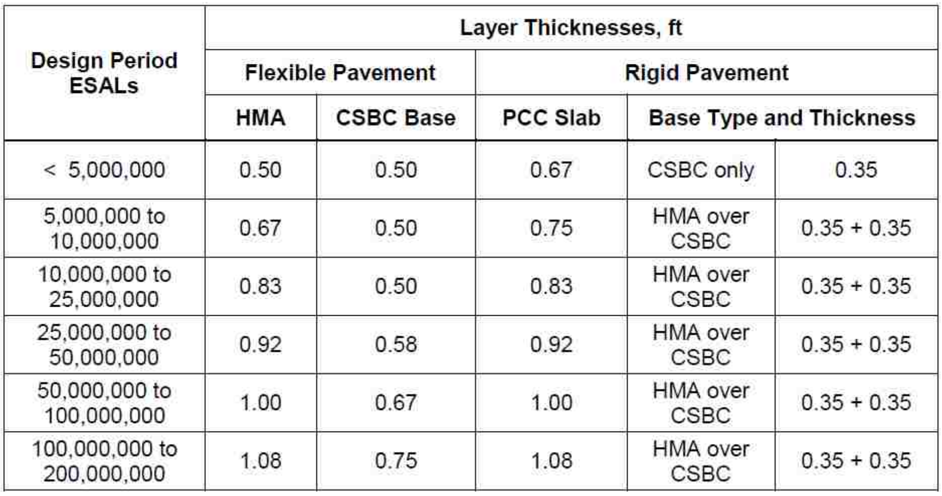
Roadprint was used to evaluate two WSDOT standard pavement designs: one HMA pavement and one PCC pavement. The functional unit was set as “a one lane-mile (one mile long and 12 feet wide) pavement.” The analyzed period was 50 years. The goal was to evaluate the environmental impacts of each standard design. Descriptions of material parameters, equipment inputs, transportation parameters, and results for all cases are in Appendix C.

4.1.1 Pavement structural design and user-entered parameters

Pavement Structural design: WSDOT standard designs for new pavements were used in accordance with the WSDOT Pavement Policy (WSDOT, 2011) for 25 to 50 million lifetime ESALs, as shown in Table 51. It is important to note that although categorized as PCC pavement in this research, the PCC pavement design also includes a HMA base layer.

The pavement structure, maintenance schedule, and activities for each design are summarized in Table 52.

Table 51 Structure of Newly Constructed Pavement (*Source:* WSDOT, 2011)



Design Period ESALs	Layer Thicknesses, ft				
	Flexible Pavement		Rigid Pavement		
	HMA	CSBC Base	PCC Slab	Base Type and Thickness	
< 5,000,000	0.50	0.50	0.67	CSBC only	0.35
5,000,000 to 10,000,000	0.67	0.50	0.75	HMA over CSBC	0.35 + 0.35
10,000,000 to 25,000,000	0.83	0.50	0.83	HMA over CSBC	0.35 + 0.35
25,000,000 to 50,000,000	0.92	0.58	0.92	HMA over CSBC	0.35 + 0.35
50,000,000 to 100,000,000	1.00	0.67	1.00	HMA over CSBC	0.35 + 0.35
100,000,000 to 200,000,000	1.08	0.75	1.08	HMA over CSBC	0.35 + 0.35

Table 52 Structural Design and Maintenance Schedule of Pavement

Design	Surface	Base	Maintenance
WA-HMA	HMA, 11 in	CSBC*, 7 in	Remove/add HMA 1.8 in, 3 times
WA-PCC	Reinforced Concrete, 11 in	HMA 4.2 in+ CSBC 4.2 in	None

*CSBC: crushed surfacing base course

User-entered parameters: These standard designs were only structural designs; hence, other necessary parameters, such as equipment and transportation, were estimated based on general practice and reasonable assumptions. For example, the HMA mix design was set at 5% bitumen, 85% crushed rock, and 10% sand by weight. The transport distance for all materials was set at 31.075 miles (50 km). Table 53 lists user-entered parameters associated with paving productivity. Table 54 shows the results for the WA-HMA and WA-PCC cases.

Table 53 Parameters for The Productivity Calculation in Two Cases

User-entered Data	WA-HMA	WA-PCC
HMA Plant Supply Rate (ton/hr)	200	200
PCC Plant Supply Rate (ton/hr)	-	325
Truck Capacity (ton)	20	20
Waiting Time at Plant (min)	10	10
Waiting Time at Site (min)	10	10
Truck Travel Speed (mile/hr)	50	50

Table 54 Paving Productivity

Productivity Results	WA-HMA	WA-PCC
HMA Paving Productivity (ton/hr)	152.12	58.08
PCC Paving Productivity (ton/hr)	-	79.40
Trucks Needed for HMA Paving	13	5
Trucks Needed for PCC Paving	-	7

In both cases, the plant supply rate is higher than the paving productivity, which means paving activity would not be interrupted by waiting for mixture, and the contractors could either boost the paving speed or lower the plant supply rate.

4.1.2 Lifecycle impact assessment

In this section, results from WA-HMA and WA-PCC are described and discussed. The complete LCIA results are listed in Table 55 and Table 56. Figure 33 to Figure 36 show energy (GJ) and GWP (CO_2-E) results in three lifecycle phases: material production, construction, and material transportation.

Table 55 LCIA Results for the WA-HMA Case

	Energy Consumption		Global Warming Potential		Acidification		Photochemical Smog		Eutrophication		Human Health Criteria Air	
Unit	Energy (GJ)		GWP(CO_2 Mg-E)		Kg SO_2		Kg NO_X		Kg PO_4		milli-DALYs/Kg	
Material Production	5535	74%	251	62%	825	19%	799	49%	77	44%	28	34%
Construction	544	7%	44	11%	235	5%	352	21%	41	23%	7	8%
Transportation	1400	19%	107	27%	3399	76%	493	30%	59	34%	47	58%
Total	**7478**		**402**		**4460**		**1644**		**177**		**81**	

Table 56 LCIA Results for the WA-PCC Case

	Energy Consumption		Global Warming Potential		Acidification		Photochemical Smog		Eutrophication		Human Health Criteria Air	
Unit	Energy (GJ)		GWP(CO_2 Mg-E)		Kg SO_2		Kg NO_X		Kg PO_4		milli-DALYs/Kg	
Material Production	4598	80%	490	84%	1544	42%	1272	70%	155	71%	113	79%
Construction	379	7%	31	5%	168	5%	257	14%	29	13%	4	3%
Transportation	800	14%	61	11%	1931	53%	281	16%	34	16%	26	18%
Total	**5777**		**582**		**3644**		**1810**		**218**		**144**	

In terms of energy use and GWP, material production has the biggest impact among the three phases. The impact of construction (equipment operations) is relatively insignificant, although substantial equipment operations are involved in both cases.

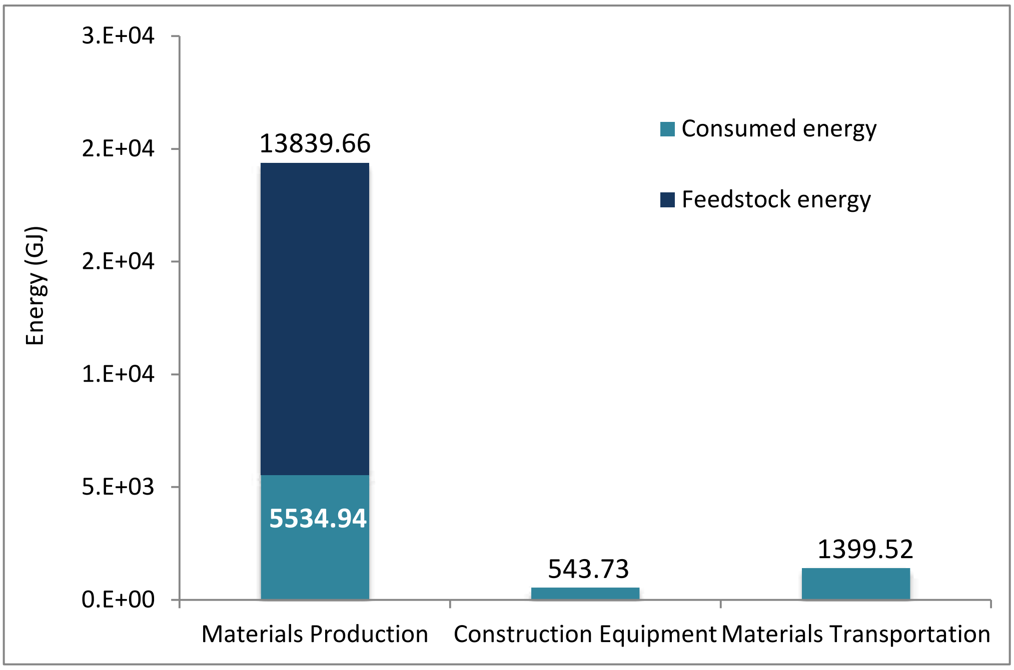


Figure 33 Energy consumptions results for WA-HMA

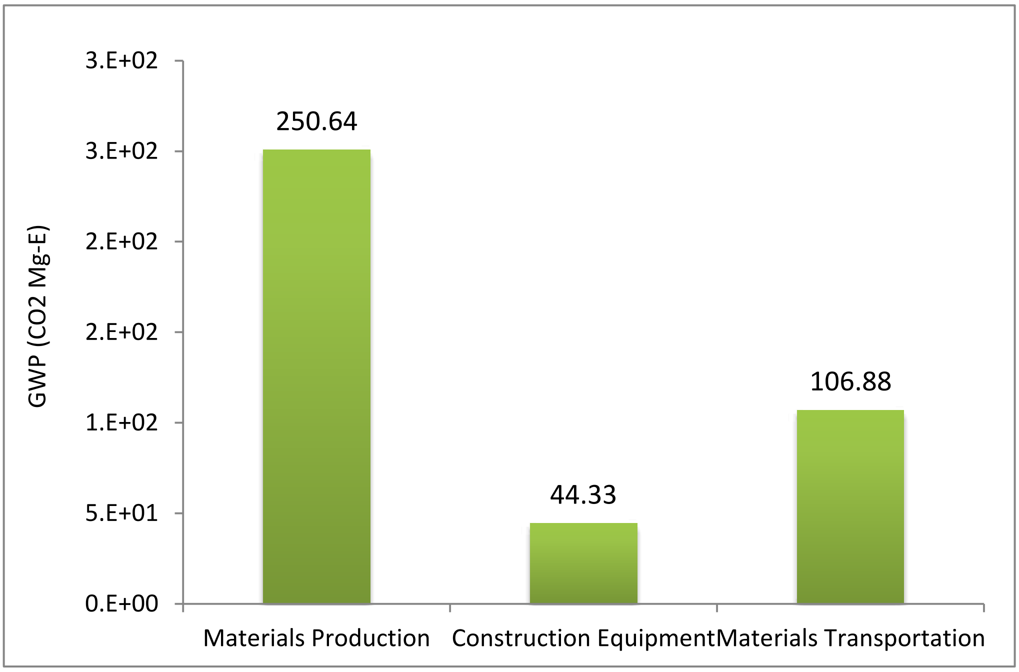


Figure 34 GWP results for WA-HMA

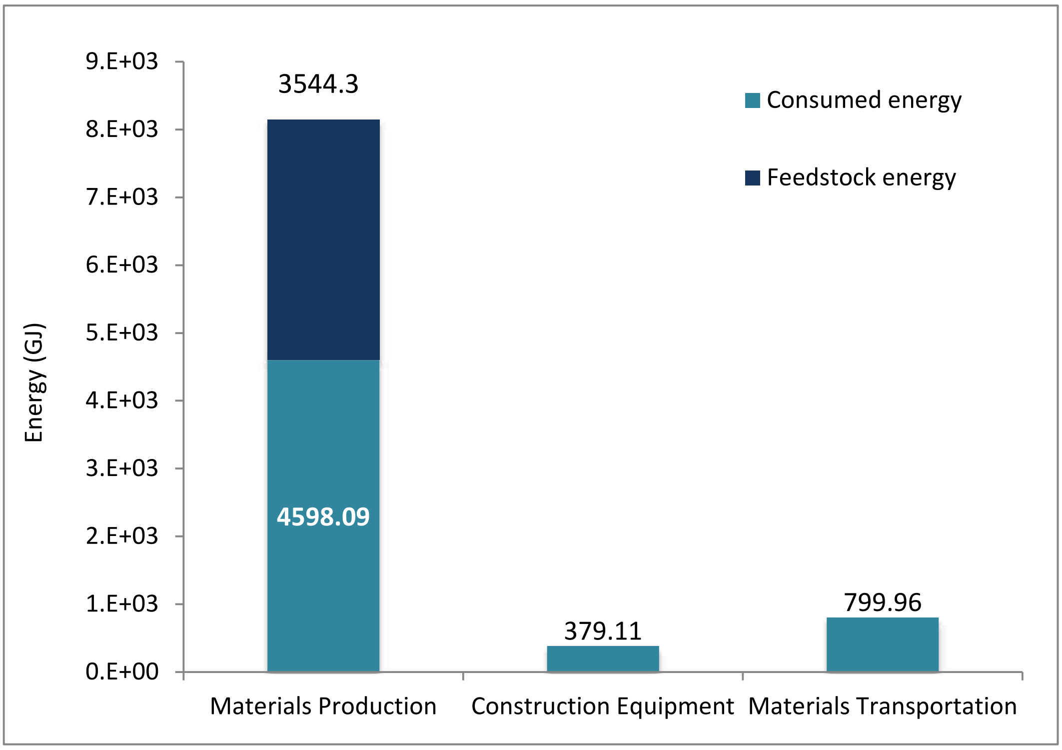


Figure 35 Energy consumption results for WA-PCC

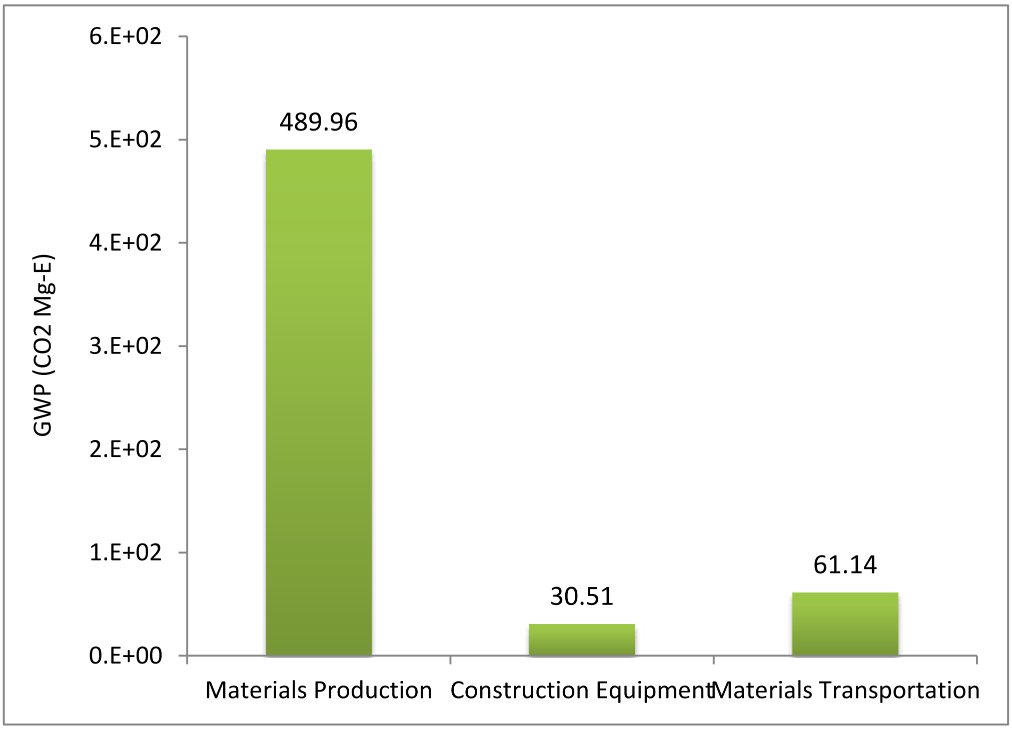


Figure 36 GWP results for WA-PCC

Table 57 shows a comparison of the energy consumption and GWP results (per lane-mile) of these two cases with the results of the 17 papers discussed in Section 2.3. Both cases show higher energy consumption and lower CO_2-E than the average reported in reviewed literature. Both cases fall within the range of the results in reviewed literature. Reasons caused the differences between results from Roadprint and literatures include: 1) different LCI data, 2) different pavement structures (thicknesses and constituents), 3) different materials, 4) different equipment usage, and 5) different transporting modes/distances, etc. For example, WA-PCC is categorized as a PCC pavement. However, a 4.2-inch HMA layer is used as a base layer in this design. PCC pavement in other studies of may have employed a different structural design in their systems boundaries (Horvath and Hendrickson, 1998; Athena, 2006; Stripple 2001; Mroueh et al., 2000; Zapata and Gamtabase, 2005).

Table 57 Comparison of Energy Use and GWP with Previous Studies (per lane mile)

	HMA Pavement			PCC Pavement		
	WA-HMA	Literature		WA-PCC	Literature	
		Average	Range		Average	Range
Energy (GJ)	7478	4320	1230-11000	5777	4420	2240-6560
With Feedstock	21318	20400	9714-26188	13431	-	-
CO_2-E (ton)	402	459	131-713	582	592	191-1220

Material Deconstruction: In both cases, material production is the most dominant in energy use and CO_2-E generation, contributing about 70%-80% of the energy consumption and 60%-70% of the CO_2-E generation. For WA-HMA, the contribution of each material to the energy/GWP of material production is shown in Table 58.

Table 58 Energy/GWP Deconstruction of Material Production: WA-HMA

	Energy* (GJ)		Energy (GJ)		GWP(CO_2 Mg-E)	
	Value	%	Value	%	Value	%
HMA/WMA	3742.8	19.3%	3742.8	68%	136.5	54.4%
PCC	0.0	0.0%	0.0	0%	0.0	0.0%
Virgin Aggregate	400.4	2.1%	400.4	7%	17.2	6.9%
Sand and Gravel	22.7	0.1%	22.7	0%	0.4	0.2%
Bitumen	1369.1	7.1%	1369.1	25%	96.6	38.5%
Feedstock	13839.7	71.4%	0.0	0%	0.0	0.0%
Cement	0.0	0.0%	0.0	0%	0.0	0.0%
RAP/RAC to Plant	0.0	0.0%	0.0	0%	0.0	0.0%
Aggregate Substitutes	0.0	0.0%	0.0	0%	0.0	0.0%
Steel	0.0	0.0%	0.0	0%	0.0	0.0%

*with feedstock included

If taken into consideration, feedstock energy in bitumen accounts for 72% of the total energy. This contribution is in the same order of magnitude as that reported in other studies. In the IVL report (Stripple, 2001) and Athena (2006), feedstock energy accounted for 46% and 69% of total energy consumption, respectively.

Without considering feedstock energy, the production of HMA consumes the most energy (68%); it also generates the most CO_2-E (54%). HMA mixture only contained 5% bitumen, but bitumen production has the second highest energy consumption (25%)

and the second highest CO_2-E (38%). Although aggregate is the major material in terms of weight, it only accounts for about 7% of total energy use and generated CO_2-E.

For the WA-PCC case, the deconstruction of material production is shown in Table 59. Cement production is the biggest contributor (48% of energy and 75% of CO_2-E), although it is only about 9% by weight in the ready-mix concrete. HMA production is again significant with respect to energy consumption (21%), whereas it only generates 7% of total CO_2-E.

Table 59 Material Energy/GWP Deconstruction for WA-PCC

	Energy* (GJ)		Energy (GJ)		GWP(CO_2 Mg-E)	
	Value	%	Value	%	Value	%
HMA/WMA	958.5	11.8%	958.5	21%	35.8	7.3%
PCC	96.9	1.2%	96.9	2%	3.2	0.6%
Virgin Aggregate	256.4	3.1%	256.4	6%	9.9	2.0%
Sand and Gravel	5.8	0.1%	5.8	0%	0.1	0.0%
Bitumen	350.6	4.3%	350.6	8%	25.4	5.2%
Feedstock	3544.3	43.5%	0.0	0%	0.0	0.0%
Cement	2200.7	27.0%	2200.7	48%	366.8	74.9%
RAP/RAC to Plant	0.0	0.0%	0.0	0%	0.0	0.0%
Aggregate Substitutes	0.0	0.0%	0.0	0%	0.0	0.0%
Steel	729.1	9.0%	729.1	16%	48.6	9.9%

*with feedstock included

Construction: For each case, certain hours of equipment operation are involved. Improving the efficiency of equipment, efficiency of equipment operation, and engines' fuel efficiency can decrease environmental impacts in this phase. However, based on the relative small contribution of equipment operations to the total impacts, these measurements would result in rather insignificant overall improvement.

Transportation: Table 60 and Table 61 show the energy consumption/GWP contribution of each material in the transportation phase for WA-HMA and WA-PCC, respectively.

For transportation, the energy/GWP results depend on the weight and transport distance of the materials. For all standard designs, 31.075 miles (50 km) was the assumed to be the transport distance for all materials. Therefore, the effect of each material on the total transportation impacts solely depended on the total weight of each material and the selected input value of 31.075 miles as the transportation distance.

The results show that HMA, PCC, and aggregate transportation make up the majority of the impact. This result is reasonable, because the distance entered for all the materials is assumed to be uniform and the mixture and the aggregates are the main materials by weight (94%). This result also points out that to minimize energy use or GHG emissions local sources for heavy and major materials should be used when possible.

Table 60 Transportation Energy/GWP Deconstruction for WA-HMA

	Energy (GJ)		GWP(CO2 Mg-E)	
	Value	%	Value	%
HMA/WMA	533.8	38.1%	40.8	38.1%
PCC	0.0	0.0%	0.0	0.0%
Virgin Aggregate	717.2	51.2%	54.8	51.2%
Sand and Gravel	53.4	3.8%	4.1	3.8%
Bitumen	27.5	2.0%	2.1	2.0%
Cement	0.0	0.0%	0.0	0.0%
RAP/RAC to Plant	0.0	0.0%	0.0	0.0%
Aggregate Substitutes	0.0	0.0%	0.0	0.0%
Steel	0.0	0.0%	0.0	0.0%
Rap/RAC Collection	67.7	4.8%	67.7	4.8%

Table 61 Transportation Energy/GWP Deconstruction for WA-PCC

	Energy (GJ)		GWP(CO2 Mg-E)	
	Value	%	Value	%
HMA/WMA	145.2	18.2%	11.1	18.2%
PCC	376.6	47.1%	28.8	47.1%
Virgin Aggregate	254.5	31.8%	19.5	31.8%
Sand and Gravel	14.5	1.8%	1.1	1.8%
Bitumen	7.5	0.9%	0.6	0.9%
Cement	0.0	0.0%	0.0	0.0%
RAP/RAC to plant	0.0	0.0%	0.0	0.0%
Aggregate substitutes	0.0	0.0%	0.0	0.0%
Steel	1.6	0.2%	0.1	0.2%
Rap/RAC Collection	0.0	0.0%	0.0	0.0%

4.2 Comparison of pavement LCA tools – standard designs

To assess the capability of Roadprint, WA-HMA, WA-PCC, and four typical Spanish highway designs were evaluated by Roadprint and four other available pavement LCA tools: OASIS, PaLATE v2.2, EIO-LCA, and PE-2. The comparison of all five tools, in terms of scope, system boundary and data quality, is shown in Table 62. Data quality scoring is based on the mechanism in described in Section 3.3.

Table 62 Tools Comparison In Terms Of Scope, System Boundary and Data Quality

Tool	Scope/System Boundary					Uncertainty Analysis	Data Quality Score
	Material Production	Transportation	Construction	Use	LCIA		
Roadprint	Bitumen Cement HMA PCC Steel Aggregate RAP Slag Fly Ash Bottom Ash Glass Cullet	Heavy Truck Medium Truck Train Sea Barge	Grader Excavator Backhoe Loader HMA Paver MTV Roller PCC Spreader PCC Paver Milling Machine PCC Crushing	N/A	Energy GWP Eutrophication Acidification Photo-smog HH Criteria	Probabilistic Analysis	3.51
OASIS (González and García, 2009)	Bitumen Cement Steel Aggregate	Heavy Truck Medium Truck	HMA Paver Roller PCC Paver Loader	N/A	Energy/CO_2	N/A	2.69
PaLATE v2.2 (Greenroads, 2010)	Bitumen Cement HMA PCC Steel Aggregate RAP Slag Fly Ash Bottom Ash Glass Cullet	Truck Train Sea Barge	Grader Excavator Backhoe Loader HMA Paver MTV Roller PCC Spreader PCC Paver Milling Machine PCC Crushing	N/A	Energy GWP	N/A	2.85
EIOLCA (CMU, 2002)	HMA PCC Steel Aggregate	N/A	N/A	N/A	Energy/CO_2	N/A	2.72

Tool	Scope/System Boundary					Uncertainty Analysis	Data Quality Score
	Material Production	Transportation	Construction	Use	LCIA		
PE-2 (Mukherjee, 2012)	Bitumen Cement Steel Aggregate	N/A	Grader Excavator Backhoe Loader HMA Paver MTV Roller PCC Spreader PCC Paver Milling Machine PCC Crushing	Traffic operation	CO_2	N/A	2.50

The Spanish designs were provided by a Spanish research assistant who visited the University of Washington in 2011. Her research topics were associated with the Spanish pavement LCA tool, OASIS. The material parameters, equipment inputs, and transportation assumptions are in Appendix C. Energy and GWP are the two impacts compared among these designs and tools. The results are shown in three phases: material production, construction, and material transportation.

4.2.1 Material production phase

Figure 37 and Figure 38 show the energy (without feedstock energy in Roadprint) and GWP comparison of the material production phase.

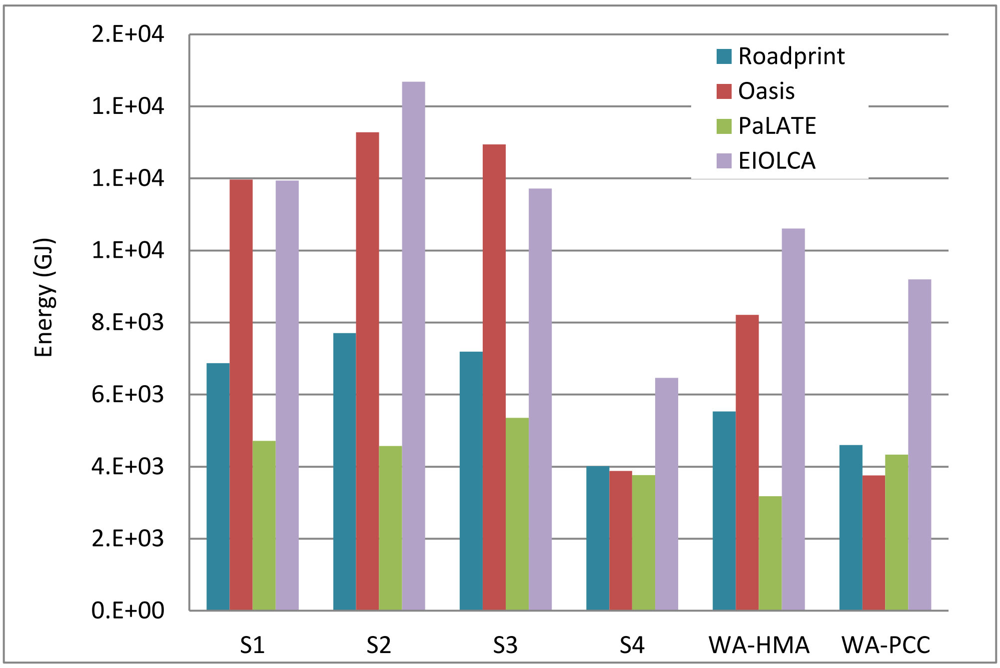


Figure 37 Comparison of energy use for material production (without feedstock energy in Roadprint)

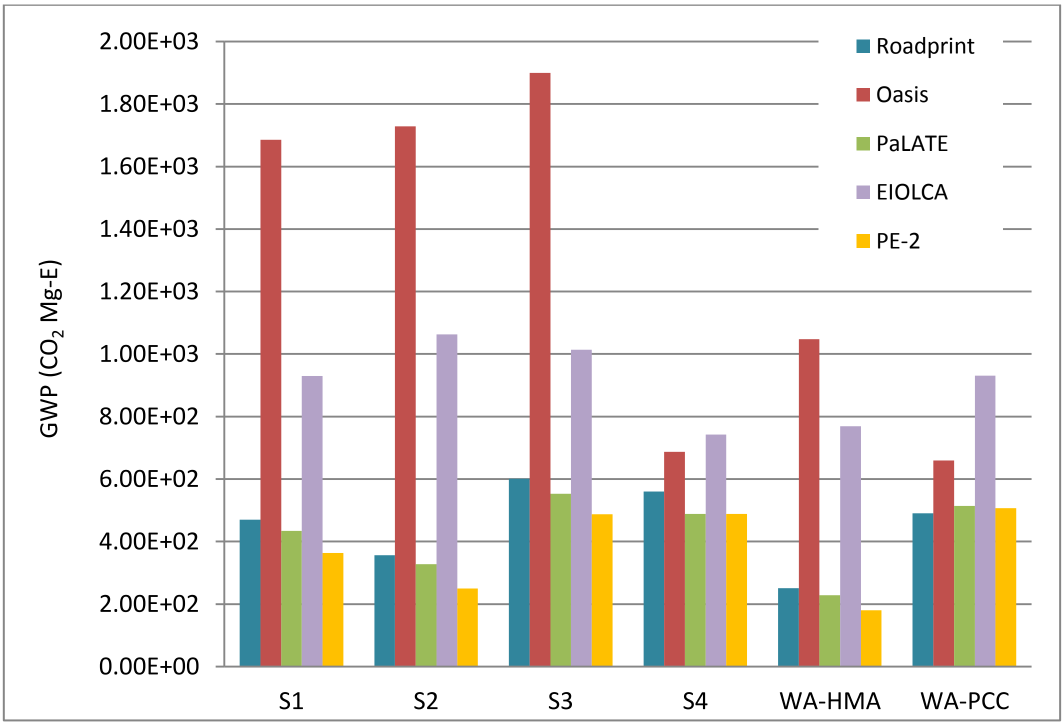


Figure 38 Comparison of GWP for material production- standard designs

For HMA pavements, Spanish 1, Spanish 2, Spanish 3, and WA-HMA, the four tools yield a consistent ratio of energy use: Roadprint: OASIS: PaLATE v2.2: EIO-LCA = 1.5:

2.6: 1: 2.8. If feedstock energy is included in Roadprint, the scale becomes 5: 2.6: 1: 2.8. For the PCC pavements, Spanish 1 and WA-PCC, the ratio is OASIS: Roadprint: PaLATE v2.2: EIO-LCA = 1: 0.95: 1: 1.9.

The energy results from OASIS and EIO-LCA for HMA are two to three times higher if the feedstock energy is not considered in Roadprint. This is mainly because the energy data for HMA maintenance used in OASIS is 20-30 times higher than that in Roadprint and PaLATE v2.2. In EIO-LCA, HMA/PCC production data in EIO-LCA is three times higher than that in Roadprint and in PaLATE v2.2, because the former does not have system boundary. In addition, the data used are subjected to issue of double counting and segregation.

The PCC's energy results with OASIS are lower, and this may be due to the fact that (1) the figure of energy data for cement production are lower than those for other tools, (2) OASIS does not include the PCC mixing process in PCC production, and (3) the energy data for steel is about one-third that of the others.

In relation to the result for CO_2-E, PE-2 is also included. The ratio of CO_2-E for Roadprint: OASIS: PaLATE v2.2: EIO-LCA: PE-2 = 1.3: 5.3: 1.2: 3.3: 1 for the HMA projects; for PCC, the ratio is 1.05: 1.3: 1: 1.7: 1. Again, the results for HMA from OASIS are obviously higher because of the same reason: the CO_2-E data of HMA maintenance is

20-30 times higher than that in Roadprint and PaLATE v2.2. The CO_2-E results with EIO-LCA are higher for both HMA and PCC, mainly because the CO_2-E data for PCC/HMA production in EIO-LCA are two to seven times higher than those in Roadprint and PaLATE v 2.2.

According to the observations, comparing HMA and PCC pavement with different tools generated different results (e.g., results of WA-HMA and WA-PCC with Roadprint and PaLATE v2.2). Thus, comparing different materials using different tools could be risky, because the differences (scope, system boundary and data sources) in tools might overshadow the differences in actual processes of items compared, potentially leading to misinterpretation of the results. Comparisons using same tool seem more advisable but there are still concerns. For each tool, the trends between the six standard designs are similar but not identical to those of other tools. For example, S2 and S3 consumed the most energy with each tool, but the order of all six designs was different in each tool. Also, the trend identified for GWP is not consistent with the trend for energy among the tools. These observations indicate that the choice of tool can influence which alternative is favorable.

4.2.2 Construction phase – equipment operation

Figure 39 and Figure 40 show the comparison of energy/GWP during the construction phase. EIO-LCA is excluded from this discussion, because it does not cover construction activities at all, and PE-2 is only included in the CO_2-E portion, because it does not calculate energy use. The energy ratio between Roadprint, OASIS, and PaLATE v2.2 is consistently 8: 4: 1. The CO_2-E ratio for Roadprint: OASIS: PaLATE: PE-2 is also consistent at 10: 15: 1: 3.   OASIS's results for energy use are generally lower than those of the other tools, but its CO_2-E results are generally higher than those of the other tools. This finding is due to OASIS using a higher CO_2/energy factor for diesel.

Although the comparison shows consistent energy and GWP trends in construction phase, the calculation logic is different in Roadprint, OASIS, PaLATE v2.2 and PE-2. OASIS does not allow the user to select the equipment for a specific project. Instead, an unchangeable set of equipment is preselected for every "unit" of material, and the equipment operations are proportional to the amount of material consumed. Roadprint and PaLATE v2.2 calculate equipment operating hours based on the capacity (or performance index) of the equipment (defined as "area by time (m^2/hr)," "speed by time (ft./min)," or "mass by time (ton/hr)"). In PE-2, users have to enter precalculated or pre-estimated operating hours for the equipment selected.

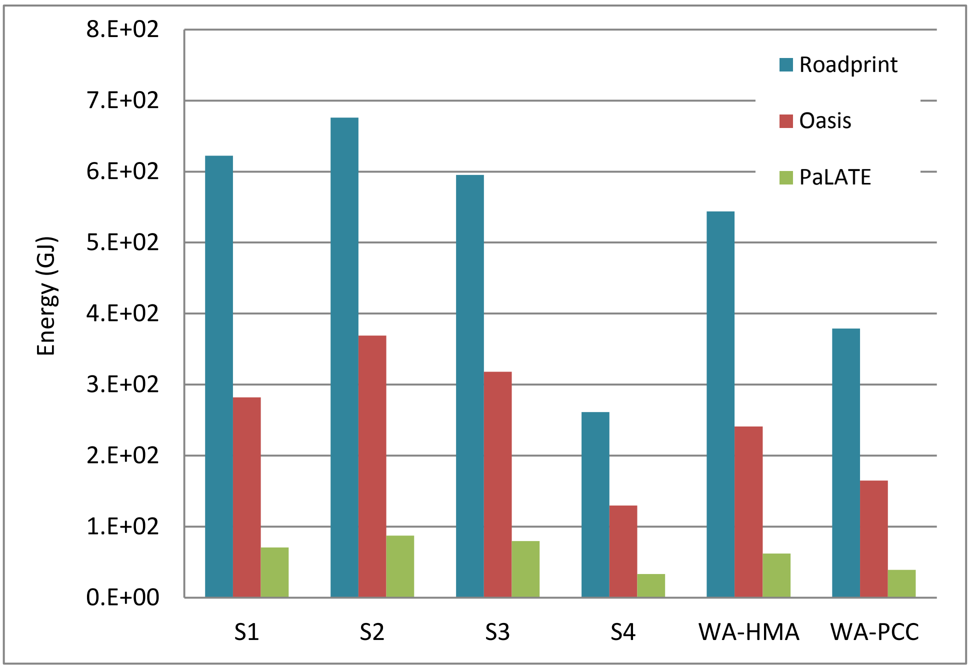


Figure 39 Comparison of energy for equipment- standard designs

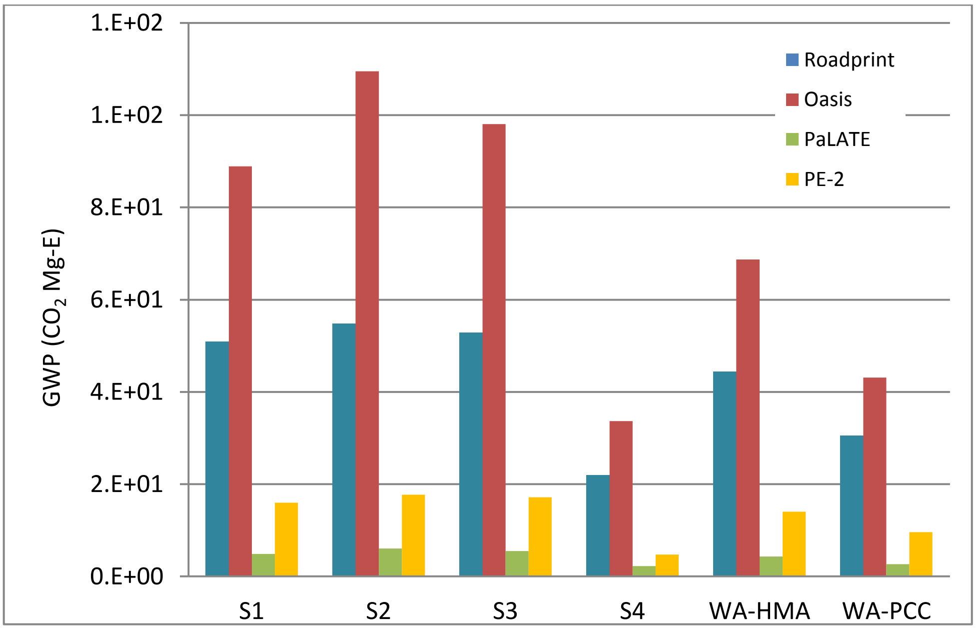


Figure 40 Comparison of GWP for equipment- standard designs

4.2.3 Transportation phase

Trucking is the only transportation mode used, and a uniform distance of 31.075 miles (50 km) is used for all cases in OASIS, Roadprint, and PaLATE v2.2. EIO-LCA does not address transportation separately, and material transportation is beyond the scope of PE-2. Figure 41 and Figure 42 show the energy/GWP comparison of the transportation phase.

The transportation impacts are determined by the mass and the transport distance of materials in Roadprint, and the same logic is applied with the two other tools. Accordingly, there is a corresponding trend in the results between Roadprint, OASIS, and PaLATE v2.2. The ratio for energy is 1.22: 1.5: 1. The ratio for CO_2-E is 1.35: 1.2: 1.

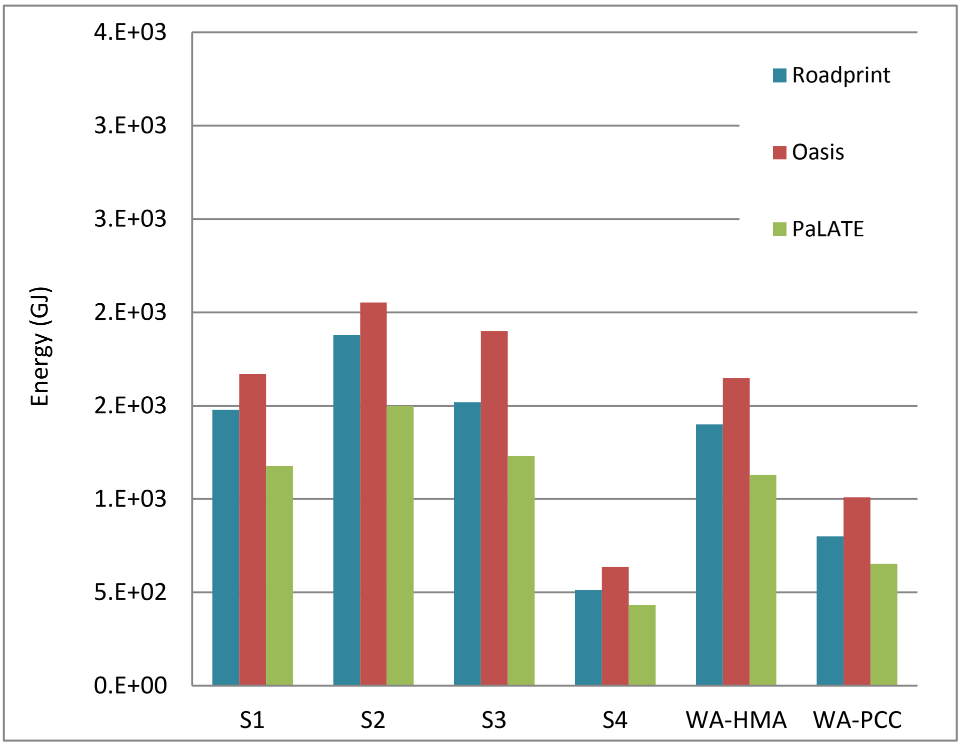


Figure 41 Comparison of energy for transportation- standard designs

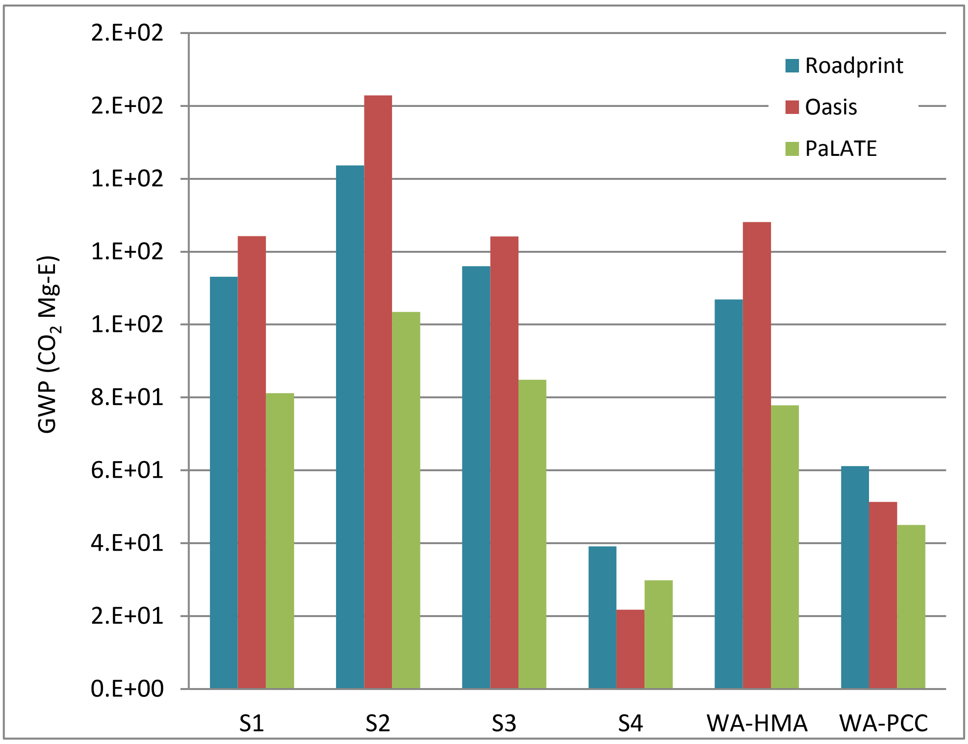


Figure 42 Comparison of GWP for transportation- standard designs

4.2.4 Overall comparison

The overall energy use and GWP of each design are shown in Figure 43 and Figure 44. The results obtained and the relationships between each tool are almost identical to those for material production because the latter is the most significant phase among the three lifecycle phases.

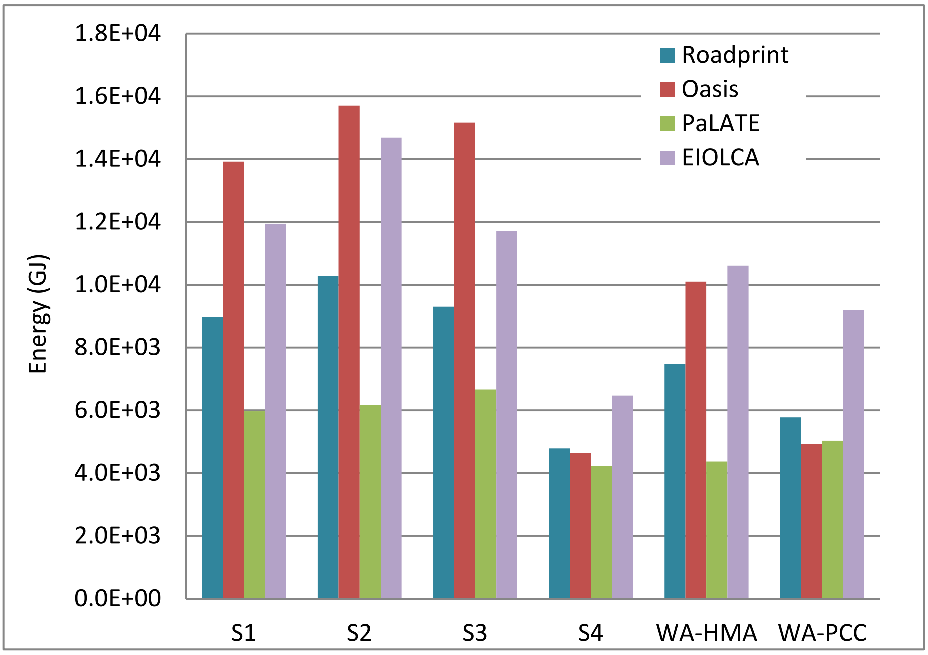


Figure 43 Energy for the entire lifecycle

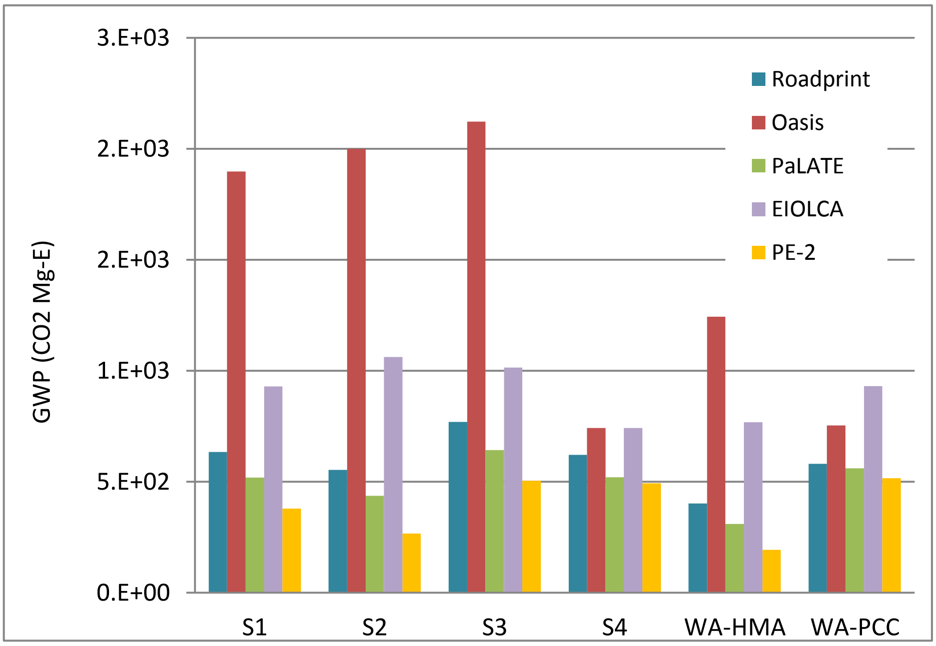


Figure 44 GWP for the entire lifecycle

4.3 Pavement LCA tools comparison - Pavement projects

In addition to the six standard designs, three projects, SR-240, US-97, and Keolu Drive, were evaluated by Roadprint and the four other pavement LCA tools. The goal was to further assess the dependability and discernibility of Roadprint by entering more diverse parameters that reflect various conditions of pavement construction.

4.3.1 Project descriptions

Sections 4.3.1.1 to 4.3.1.3 provide the general information about each project. Please see Appendix D for more detail.

4.3.1.1 Keolu Drive, Hawaii

General description: This project was composed of two sections: Wanaao Rd. to Akaakaawa St. and Kalanianaole Hwy to Akahai Street, in Kailua, HI. The general scope was to mill 6 inch of existing HMA pavement (total 13,188 yd^3) on a collector road and then resurface with 2 inch asphalt concrete pavement (ACP) over 4 inch of asphalt concrete base (ACB), both considered HMA for the purposes of this analysis. The location is shown in Figure 45.

Materials: During initial construction, this project used 9,516 tons of ACP and 18,790 tons of ACB. The ACP mix contained 5.5% bitumen and 94.5% crushed stone, whereas the mix design for ACB was 5% bitumen, 10% cullet, and 85% crushed stone. For maintenance, the mix design was the same as ACP, and the total tonnage was 7,913 tons.

Transportation: The transport distance of HMA, crushed stone, and RAP was 6 miles. Asphalt cement was originally supplied from a refinery in New Brunswick, Canada, shipped to a terminal at Kalaeloa Harbor, and then trucked to the HMA plant. The transportation distance for the asphalt cement was set as the distance from the Kalaeloa Harbor terminal to the HMA plant, approximately 30 miles.

Maintenance: Maintenance included 2 inch ACP mill-and-fill in year 10, 20, 30, and 40.

Figure 45 Project map of Keolu Drive

4.3.1.2 US-97, Lava Butte - South Century Drive, Oregon

General description: This project was located in central Oregon along US-97. This project increased the capacity of US-97 by converting the existing two-lane highway into a four-lane (two in each direction) highway. Two inches of the existing surface were removed before paving. Construction began in April of 2009 and will be completed in the fall of 2012. The location is shown in Figure 46.

Materials: The expansion of US-97 used 96,600 tons of HMA and 113,000 tons of plant mix aggregate base. The HMA mix design contained 6.16% bitumen, 20% RAP, and 73.4% crushed stone. RAP was also used for 30% of the total base material.

Transportation: The aggregate source was 4 miles away from the HMA plant, and the bitumen supplier was 30 miles away from the HMA plant. The transportation distance for all other materials was assumed to be 30 miles.

Maintenance: The assumed maintenance schedule was to add 2 inches of HMA wearing course every 15 years.

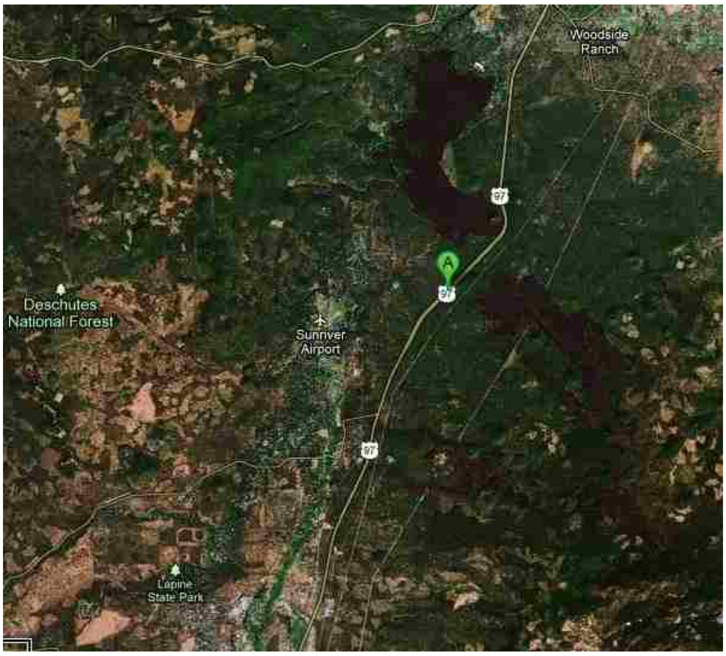


Figure 46 Project map of US-97

4.3.1.3 SR-240, I-182 to Columbia Center I/C, Washington

Project description: This was a newly constructed PCC project that added additional lanes to the SR-240 between Richland and Kennewick, Washington. The project began in May 2005 and was completed in June 2007. The location is shown in Figure 47.

Materials: The SR-240 used 65,090 tons of HMA, 39,830 CY of ready-mix concrete, 185,690 tons of CSBC, and 68,100 dowel bars. This project used 4,500-psi ready-mix concrete for the PCC pavement. There was no available information on the HMA mix design, and it was assumed that it used 5% bitumen, 10% sand, and 85% crushed stone.

Transportation: This project used a temporary PCC plant only 0.5 miles away from the jobsite. The HMA mixing facility was 12 miles away from the jobsite. Other than that, there was no available data on material transportation. The transportation distance for other materials was assumed to be 50 km (31.075 miles).

Maintenance: No maintenance was scheduled for this project.

Figure 47 Location of project SR-240

4.3.2 Material production

These three projects differed in scale. The total materials usage of each project is shown in Table 63. The US-97 consumed the most materials in terms of weight, the SR-240 consumed a little less, while Keolu Drive used only about one-third of materials utilized by two other projects. The comparisons of energy use without and with feedstock energy are shown in Figure 48 and Figure 49. Figure 50 shows the GWP results of this phase.

Table 63 Materials Used (tons) For Each Project

Material	Keolu Drive	US-97	SR-240
Bitumen	3,203	9,724	3,255
Cement	-	-	10,430
Virgin aggregate	54,875	248,266	281,443
Sand	-	-	31,735
RAP used in project	-	67,749	-
Steel	-	-	336
Cullet	1,879	-	-
HMA	59,957	164,310	58,581
PCC	-	-	76,083
Subtotal (ton)	119,914	490,049	461,863
RAP to collect	57,962	20,391	-
Total (ton)	177,876	510,440	461,863

The inclusion of feedstock energy made the energy resulted in a two to threefold increase in energy consumption, based on the percentage of bitumen in total materials.

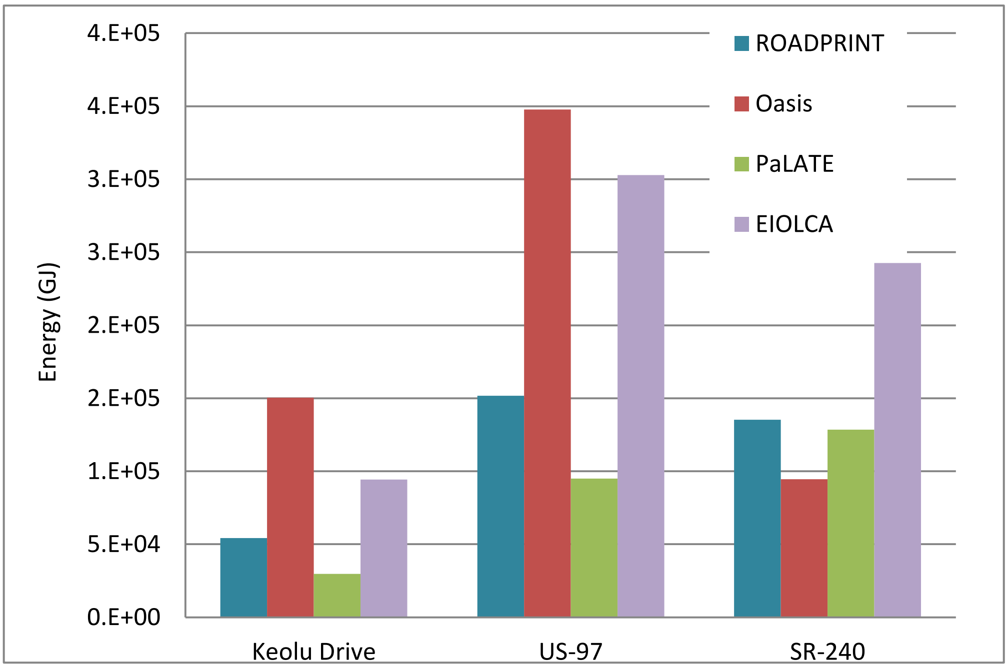


Figure 48 Comparison of the energy use in material production- no feedstock energy

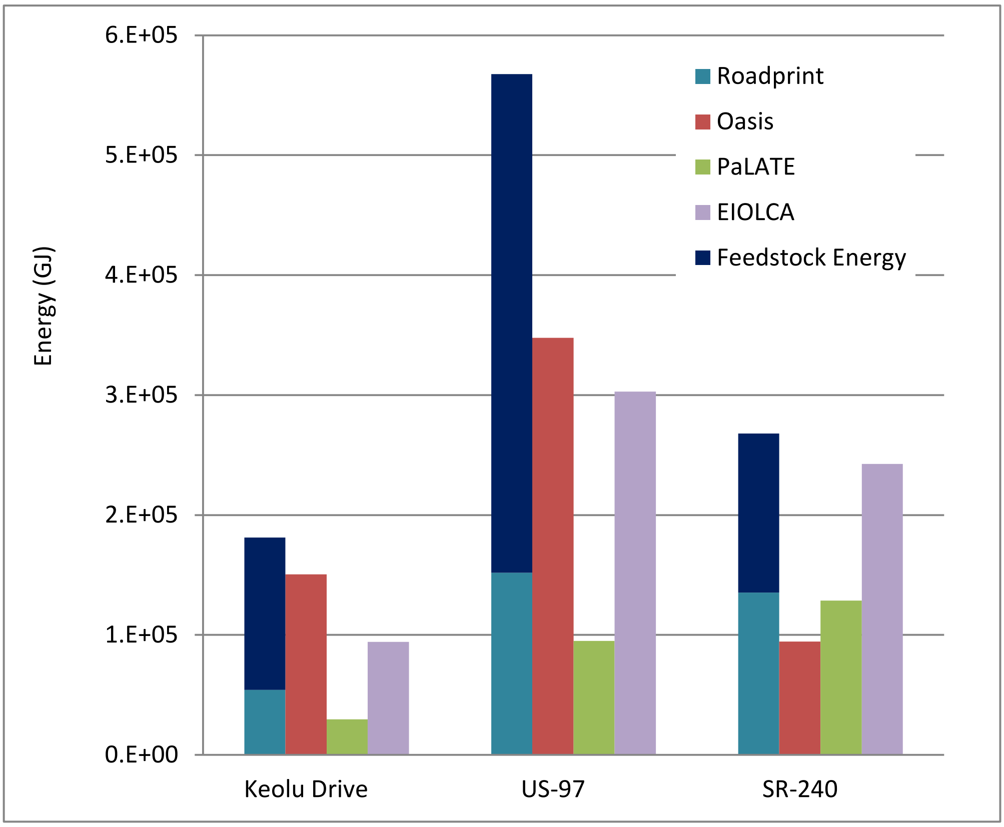


Figure 49 Comparison of energy use in material production- with feedstock energy

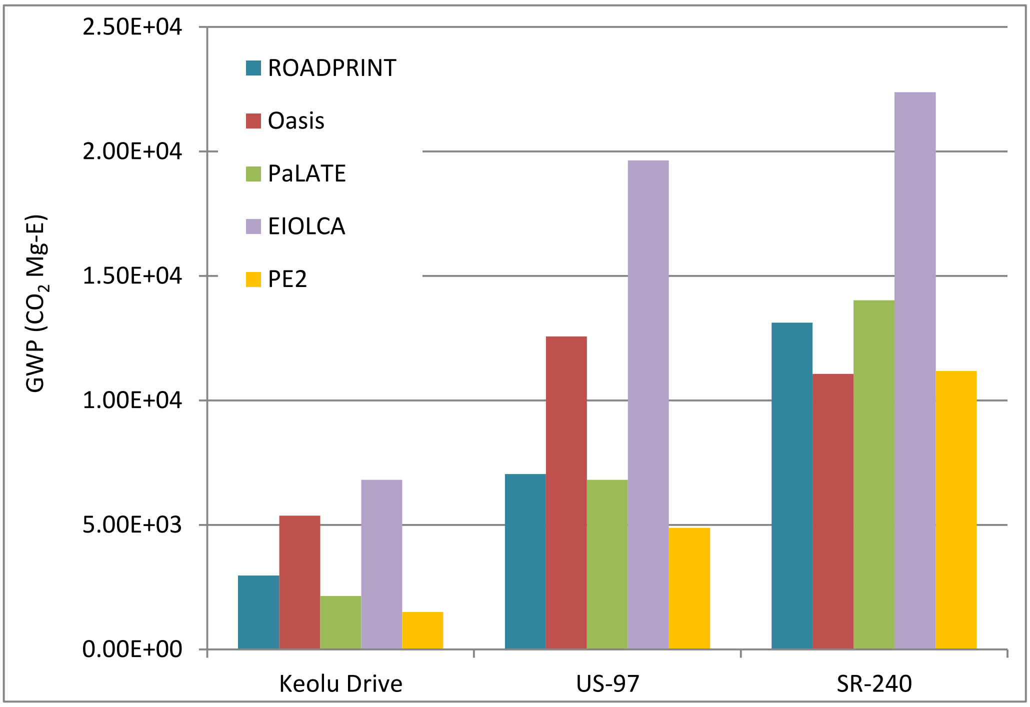


Figure 50 Comparison of GWP in material production

The energy consumption and GWP generation of each tool were approximately proportional to material usage in tonnage. However, SR-240's GWP results from Roadprint, PaLATE v2.2, EIOLCA, and PE-2 were higher than the GWP for US-97; even though the SR-240 consumed fewer materials. The increased GWP was caused by the data values of major materials, as listed in Table 64. The CO_2 emission for PCC production is about six times higher than HMA production. Therefore, the GWP of SR-240 was higher than that of US-97. The same explanation is also applicable to the energy result for PaLATE v2.2.

Table 64 Data For Major Materials With Different Tools

	Energy (MJ/kg)				CO2 (g/kg)			
	Cement	Bitumen	PCC	HMA	Cement	Bitumen	PCC	HMA
Roadprint	4.80	4.71	0.61	0.48	927.00	233.00	117.80	15.00
OASIS	3.60	2.09	-	-	794.00	307.00	-	-
PaLATE v2.2	5.46	2.35	-	-	851.30	171.00	-	-
EIOLCA	5.46	2.35	1.34	1.33	851.30	171.00	156.60	96.90
PE-2	-	-			841.00	157.00	102.60	11.10

4.3.3 Construction phase – equipment operation

The energy/GWP comparison results of construction phase are shown in Figure 51 and Figure 52. Theoretically, the construction impacts of each project should be proportional to the project's consumption of materials. However, Keolu Drive involved a substantial milling machine operation, which is very energy and CO_2 intensive. Therefore, the results were not completely proportional to the material consumption.

The energy ratio between Roadprint, OASIS, and PaLATE v2.2 was consistently 6: 2.5: 1.

The CO_2-E ratio was also consistent: Roadprint: OASIS: PaLATE: PE-2 = 6: 10: 1: 2.

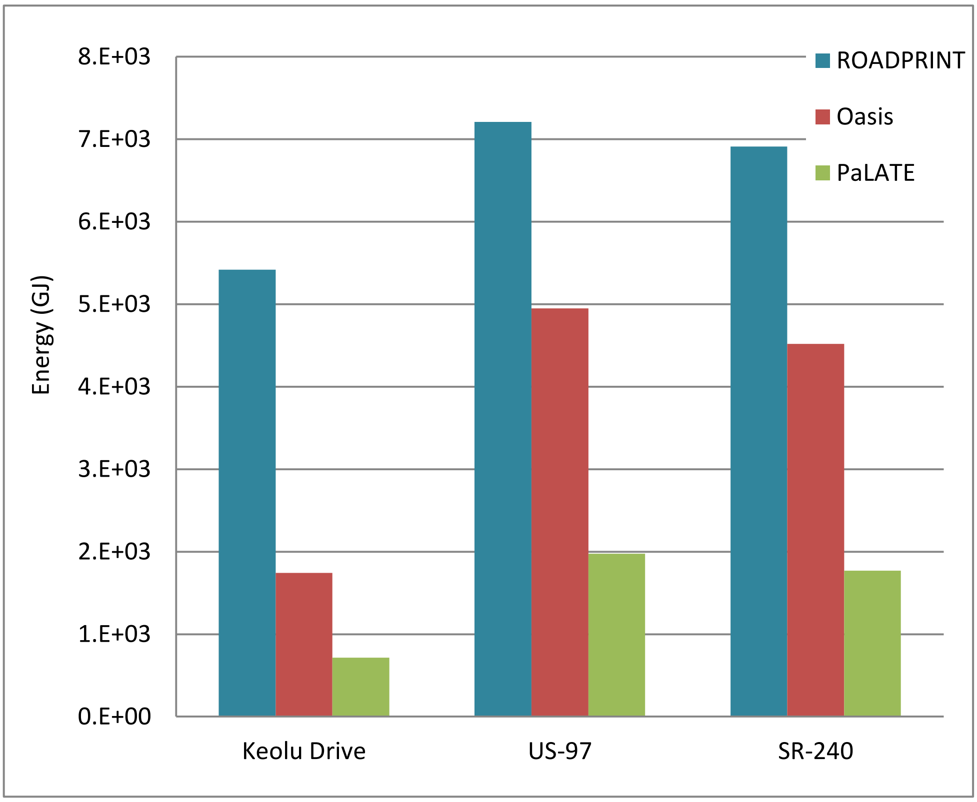


Figure 51 Comparison of energy use in construction

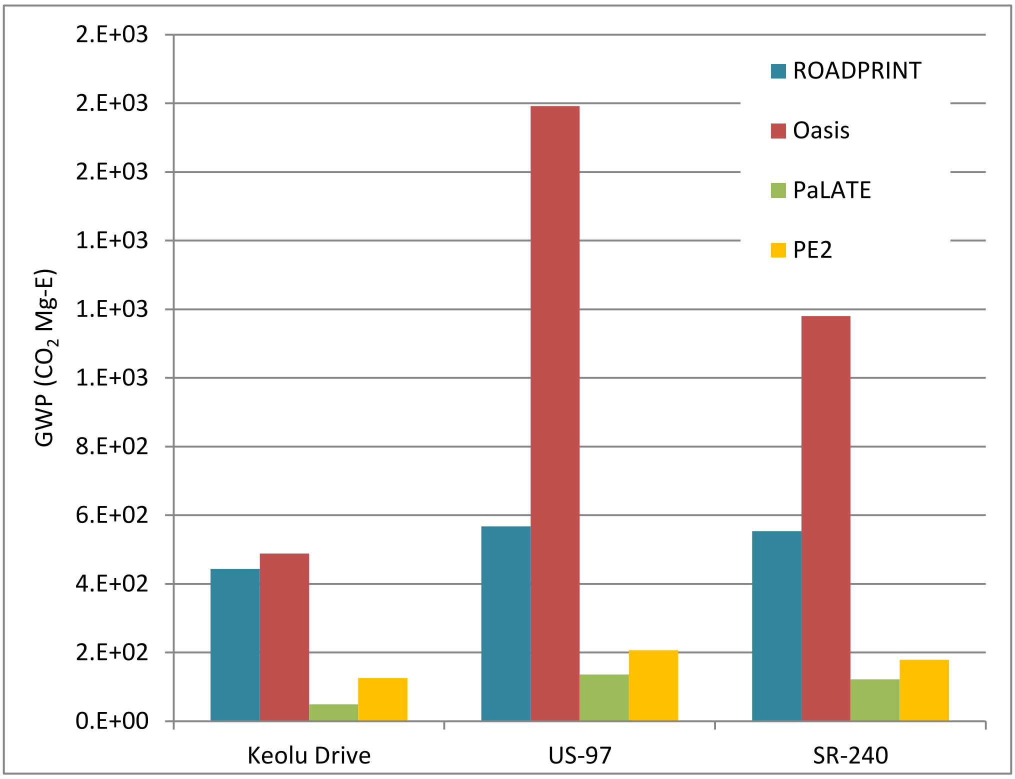


Figure 52 Comparison of GWP in construction

4.3.4 Transportation phase

Transportation is affected by the mass and the transport distance of all materials used. Table 65 shows the individual and overall "ton-mile" for each project. Figure 53 and Figure 54 show the energy/GWP comparison in the transportation phase.

Theoretically, the results for the three projects should be proportional to the corresponding "ton-mile" and Roadprint, OASIS, and PaLATE v2.2 should show the same relationship for the three projects. However, OASIS's results are questionable, with the energy for US-97 apparently lower than the energy in SR-240.

Table 65 Transportation (ton-mile) for Major Materials

	Keolu Drive			US-97			SR-240		
	Mass (ton)	Distance (mile)	Ton-mile	Mass (ton)	Distance (mile)	Ton-mile	Mass (ton)	Distance (mile)	Ton-mile
Bitumen	3,203	30	96,090	9,724	30	291,720	3,255	31	100,905
Virgin Agg.	54,875	6	329,250	248,266	4	993,064	241,016	31	7,471,496
Sand	-	-	-	-	-	-	6,509	31	201,779
RAP used	-	-	-	67,749	30	2,032,470	-	-	-
Steel	-	-	-	-	-	-	336	31	10,416
Cullet	1,879	6	11,274	-	-	-	-	-	-
HMA	59,957	6	359,742	164,310	30	4,929,300	58,581	12	702,972
PCC	-	-	-	-	-	-	76,083	0.5	38,042
Subtotal	119,914	-	796,356	490,049	-	8,246,554	385,780	-	8,525,610
RAP Collected	57,962	6	347,772	20,391	30	611,730	-	-	-
Total	177,876	-	1,144,128	510,440	-	8,858,284	385,780	-	8,525,610

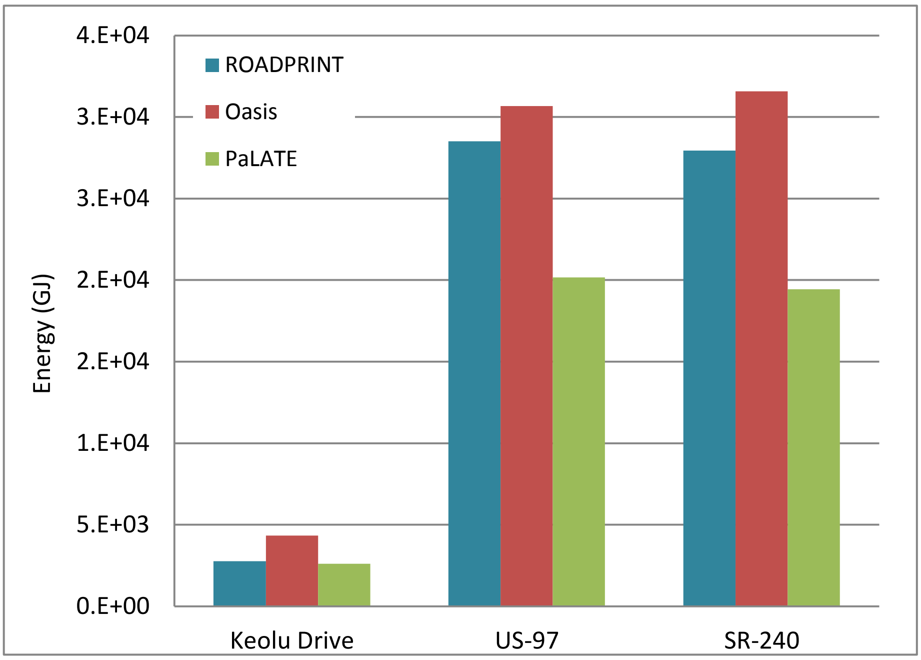


Figure 53 Comparison of energy use in transportation

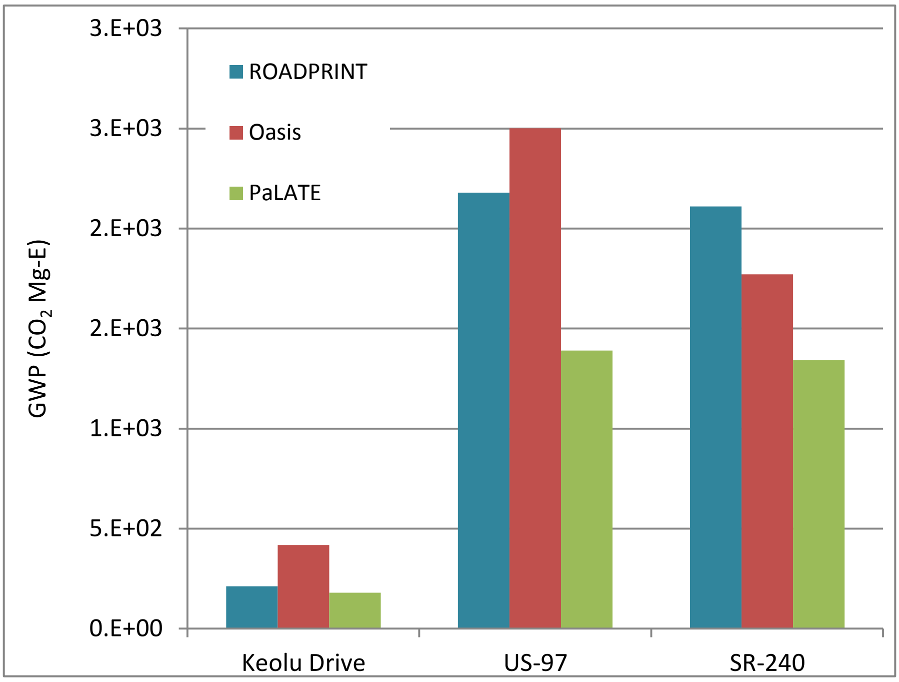


Figure 54 GWP in transportation

One reason for the inconsistent observation with OASIS is that it does not include RAP transportation, but RAP transportation accounted for about 30% and 37% of total transportation in Keolu Drive and in US-97, respectively. Figure 55 and 56 distinguish the portion of RAP in total transportation energy/GWP for Roadprint and PaLATE v2.2. For a fair comparison, RAP was assumed to account for additional 30% of total transportation in OASIS for both projects. After including RAP transportation in OASIS, its energy use for US-97 is higher than that for SR-240.

Another observation is for SR-240, the GWP with OASIS was lower than that with Roadprint, which is opposite to the other projects. The reason is unknown, because the calculation and data sources of this process is not transparent in OASIS.

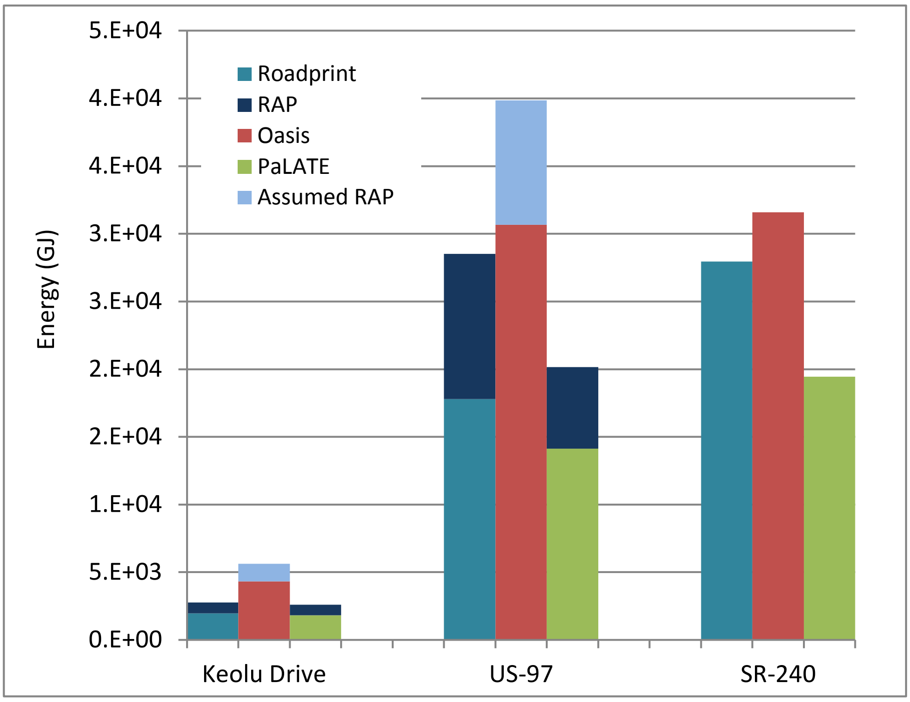


Figure 55 Energy for transportation with RAP transportation distinguished

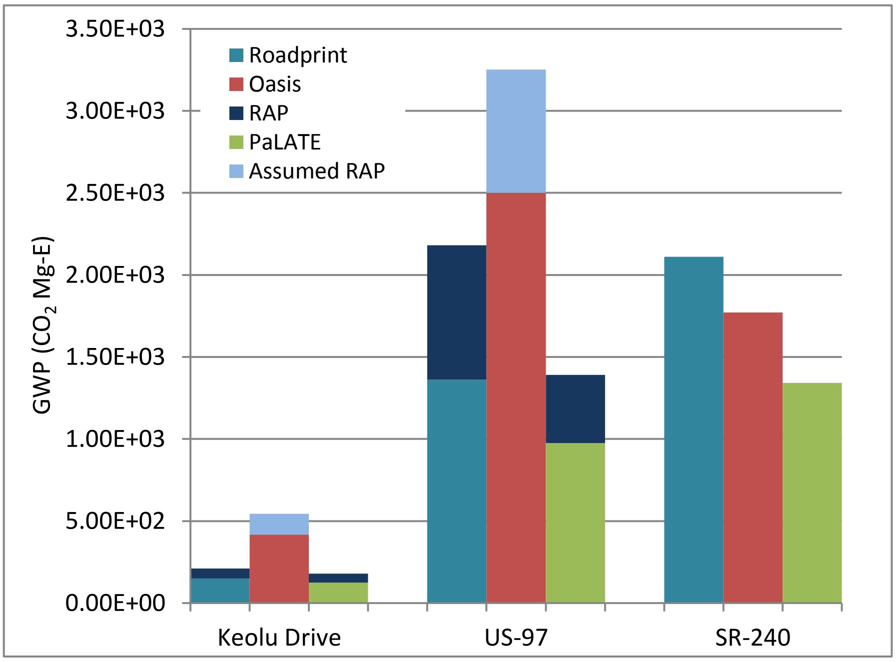


Figure 56 GWP for transportation – with RAP transportation distinguished

4.3.5 Overall comparison

The overall impacts of each project are shown in Figure 57 and Figure 58. As in Section 4.2.4, the results and the relationship between each tool were almost identical to those obtained for material production because the latter is the most significant among the three lifecycle phases.

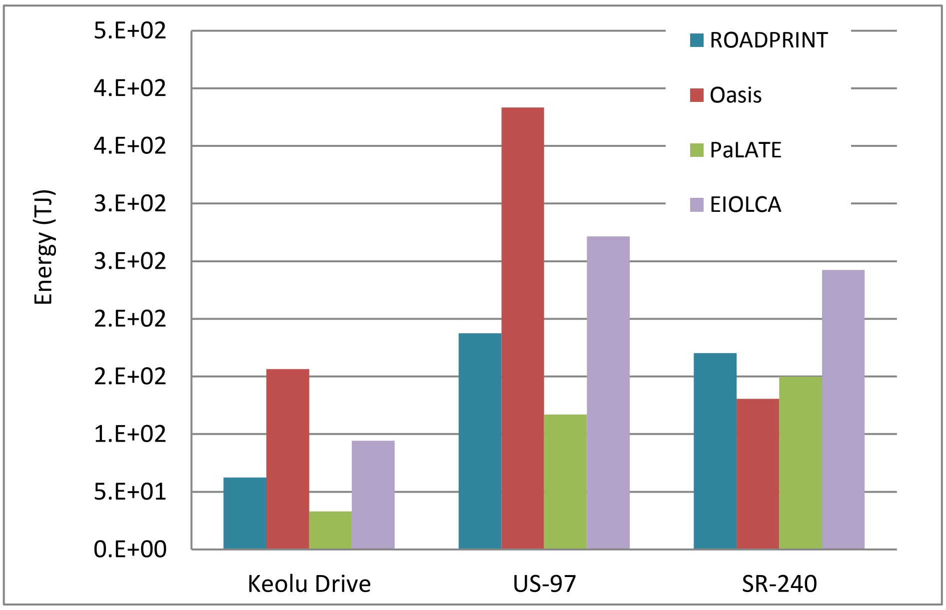


Figure 57 Comparison of energy for entire lifecycle

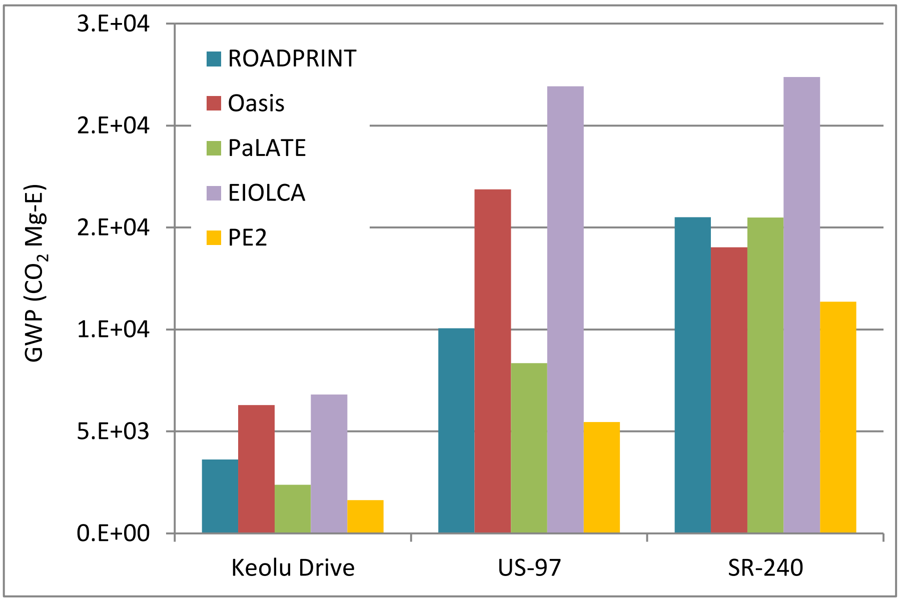


Figure 58 Comparison of GWP for entire lifecycle

4.4 Summaries

This Chapter described how Roadprint was tested and assessed by reasonable proxy of validating processes. Conclusions can be drawn from three perspectives: Roadprint performance, pavement LCA and LCA/tools comparisons.

4.4.1 Roadprint Performance

The reliability of Roadprint was assessed by comparing its results with those reported in the literatures (66 assessments in Section 2.3). The findings showed Roadprint's results are not exceptional but in the same order of magnitude as those in reviewed literature.

Roadprint was then compared with other available tools. The comparisons of material production, equipment operation, and transportation showed that although the Roadprint's results always differed from those of other tools, a consistent ratio existed between Roadprint and those tools. The difference between those tools may be due to: 1) different system boundaries being used, such as OASIS does not include RAP transportation; 2) different data sources, e.g., the difference in energy between cement and bitumen production varies in each tool; 3) nontransparent processes, such as HMA maintenance in OASIS and equipment in PaLATE v2.2.

In general, Roadprint appeared to be better at differentiating projects with different scenarios because it exhibits superior data quality, transparency, a more complete scope and a more comprehensive system boundary.

4.4.2 Pavement LCA

Material production was the most dominant phase in terms of energy consumption and GWP generation. This observation indicates that improving the material production processes would be the most efficient way of mitigating the environmental impacts from pavement construction.

When taken into account, feedstock energy could comprise about 70% of energy consumption in Roadprint. It has such a dramatic effect on the results that it would likely affect the decision. Therefore, users who employ pavement LCAs to assist their decision-making should be clear on whether feedstock is included in the system boundary. The data value of feedstock energy in bitumen is still undetermined (Häkkinen and Mäkelä, 1996; Athena, 2006; IPCC, 2006; Hammond and Jones, 2008). Therefore, the interpretation of energy results would be clearer if the feedstock data value used is elaborated upon those who conduct LCAs.

4.4.3 Comparison of LCA results with different tools

Comparing environmental impacts of different materials could be risky, even within the same tool, because the result will completely depend on the system boundary and data sources. Despite these risks, industry advocates continue to perform LCA comparisons between pavement options, particularly comparing HMA and PCC pavements. The results are typically reported as a single deterministic number, and no explanation of the variability in the data quality or the source is given (PAIKY 2010; Van Dam et al., 2012). The results from this research concerning data sources, data ranges, input variability, probabilistic analysis, and comparison of tools on a single project as well as comparison of different projects using the same tool all indicate that users have to be aware of the system boundary, data sources and limitations while using LCA tools to compare design, material and parameter alternatives.

Chapter 5. Conclusions and Recommendations

The goal of this research was to allow pavement professionals to quantitatively evaluate environmental impacts of different design and construction alternatives for pavement projects. To fulfill this goal, a pavement LCA tool, Roadprint, was developed. Roadprint is a process-based LCA tool based on a well-defined scope that uses the best available data sources for U.S. projects. Roadprint was then assessed using six standard pavement designs, three case studies and through comparison with four other pavement LCA tools. The following sections summarize this research's contributions, conclusions, and recommendations for future research.

5.1 Contributions

5.1.1 Define a comprehensive scope and a system boundary for pavement LCA

At present, there is no standard scope or system boundary to implement pavement LCAs. After reviewing current pavement LCAs, an adequate scope with a reasonable system boundary was established in this research, as shown in Figure 59. In this research, the scope concentrated on pavement construction alone. Notably, it did not include the use phase that is listed in UCPRC (2011). Energy consumption, the GWP, acidification, eutrophication, photochemical smog and human toxicity are determined impact indexes, which are believed to be helpful in the evaluation of environmental impacts.

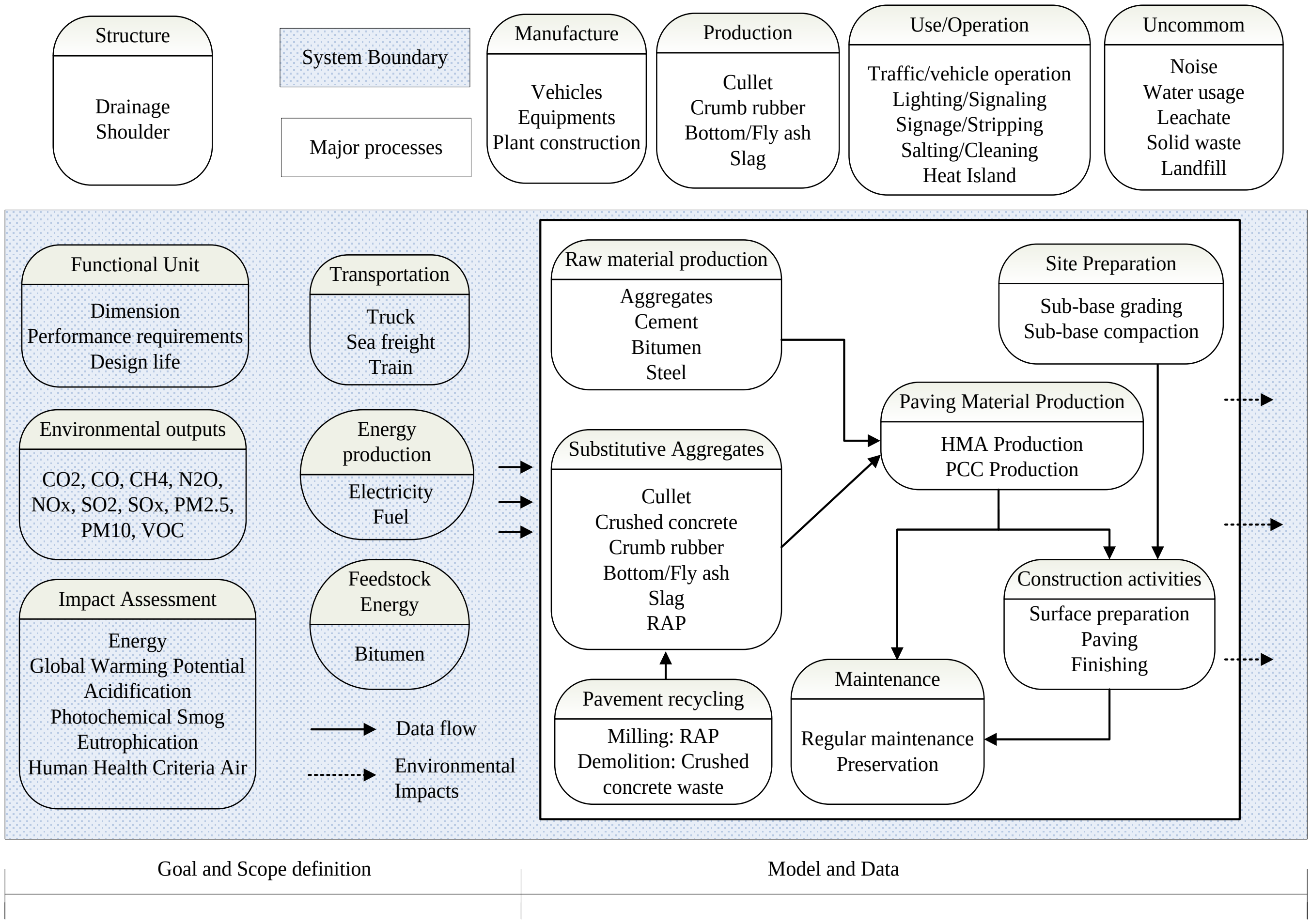


Figure 59 Proposed system boundary for pavement LCA

5.1.2 Identify and structure a suitable data inventory for pavement LCA

This research searched and reviewed available data sources and identified the most robust data to use in an LCI inventory database for pavement LCAs. The data were selected using the data quality scoring mechanism, which includes the following criteria: time relativeness, geographic proximity for U.S. projects, and transparency on data sources and boundary, and the measuring approach (ISO, 2006; Cooper and Kahn, 2012). Data sources and quality score are shown in Table 67 and Table 68. All the data used are publically available so they can be accessed by practitioners if necessary.

Table 66 Selected Data Sources For The Proposed Pavement LCA

Data	Source
Energy/electricity generation	GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model), 1.8d 2010
Energy Mix	eGrid 2007 Version_1 year 05 aggregate Excel File, Sheet ST05
Transportation	GREET UWME Extracted 2008
Construction Equipment	EPA Nonroad Model 2008
Bitumen Production	Eurobitume Eco Profile for Paving Grade Bitumen 1999
Cement Production	LCI of Cement, PCA 2006, Table 15b
Aggregate Production	Energy: LCI of PCC PCA 2007, Table 10; Emission: IVL 2000, pg. 47
Sand/gravel Production	Energy: LCI of PCC PCA 2007, Table 11; Emission: IVL 2000, pg. 48
PCC Production	LCI of PCC PCA 2007
HMA Production	EPA AP-42, Fifth Edition, Compilation of Air Pollutant Emission Factors, Ch. 11 (energy: Stripple 2001)
Steel Production	GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model), 1.8d 2010
Impact Assessment Factor	
TRACI	The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, 2002
FRED	Framework for Responsible Environmental Decision-Making, 2000

Table 67 Data Quality Score For The Inventory In Roadprint

(Scoring Mechanism: Cooper and Kahn, 2012)

Category	Bitumen	Cement	Agg.	HMA /WMA	PCC production	Dowel/tie bar production	Cullet	Equipment	Transport	Energy
Time	5	5	3.5	3	5	5	4	4	5	5
Geography	1	3	2	2	3	3	1	5	3	4
Precision, completeness	5	4	4	4	4	3	2	3	4	4
Consistency and reproducibility	3	3	3	3	3	3	3	4	3	4
Average	3.5	3.75	3.125	3	3.75	3.5	2.5	4	3.75	4.25
Overall avg.	3.51									

5.1.3 Pavement LCA tool creation

A pavement LCA tool, Roadprint, was developed based on the proposed system boundary and data inventory. Compared to existing LCA tools Roadprint can better differentiate between project alternatives because:

(1) It is process-based. This allows the specification and inclusion of significant sub-processes such as the inclusion of RAP and industrial byproducts at varying amounts, specific HMA mix designs, the value used for bitumen feedstock energy, and the use of WMA.

(2) Users can enter specific parameters to better describe project's situations. Users can specify transportation distances for each material, and project location (in order to better describe the electricity mix associated with the project).

(3) Construction productivity is modeled. Roadprint allows users to enter specific equipment parameters, and to calculate operating hours and paving productivity. The computed operating hours are more precise than other tools and the productivity information can be used for project planning.

(4) It provides output tailored to pavement professionals. Output of categories of materials production, construction and transportation help pavement professionals

understand where energy and emissions are generated according to typical industry categories, and which of these categories they can affect at the project level.

(5) Roadprint includes a proof-of-concept probabilistic analysis. Although this function still has limitations, it allows users to evaluate parameter uncertainty and variability.

Roadprint allows pavement practitioners to conduct pavement LCAs in a more efficient way: users do not have to have specialized LCA knowledge and can skip the resource and time consuming process of data collection.

5.2 Conclusions

5.2.1 Comparison of tools

Roadprint is capable of distinguishing differences among various pavement projects using both deterministic and probabilistic approach. Past LCA tools have focused only on the deterministic method, but there are many variations that exist in projects and Roadprint can capture these using different design and user-entered parameters and materials. The findings of this dissertation show that the outcomes of Roadprint are of the same order as those from other studies and tools.

Comparing processes that use different tools is not reasonable because the outcomes are based on different measures, scopes, and system boundaries. The differences in the tools may actually overwhelm the differences in the actual process, leading to a misrepresentation of the outcomes. Using one tool to compare alternatives is obviously better but there are other risks involved such as data quality and data uncertainty. When and how to measure data for a process as well as what data have been measured and reported, could also lead LCA comparison to different results. Before conducting a LCA or employing LCA results, the scope, system boundary and data quality must be carefully considered and verified so that they are compatible with the goals of that LCA.

5.2.2 Conclusions on pavement LCAs

The analyses in Chapters 3 and 4 showed that materials production dominated the energy and GWP results and accounted for 65-90% of energy use and $C0_2$-E generation. HMA, bitumen, cement and steel were the most influential materials in material production, accounting for 80-90% of energy use and $C0_2$-E generation.

Construction, which is essentially workzone equipment operation, only contributed 2-7% in total energy use and CO_2-E generation in the three lifecycle phases. This is consistent with other studies (Stripple, 2001; Mroueh et al., 2001; Weiland, 2008). However, this might change if the scope of LCA expanded to the entire roadway construction, which could involve more intensive equipment, such as tunnel boring machine and drilling machine for bridges.

Feedstock energy had a huge impact on the energy results, potentially increasing reported total energy use two to threefold. It must be clear whether an LCA includes feedstock energy in its results because the inclusion of this parameter could lead to different evaluations. A suggestion is to label feedstock energy individually in the results so users can clearly identify its presence and quantity.

The probabilistic analysis shows there is relatively high variation among the materials and material production and a good next step for this research is to understand why this variation may exist. When the standard deviation was assumed to be 0.05μ, only slight variation in the probabilistic results was observed for user-entered parameters. Consequently, uncertainty in relation to material production was most influential in terms of energy and GWP, and even higher than the combination of construction and transportation phases.

5.3 Recommendations

Recommendations are addressed from four perspectives: LCA scope, data inventory, LCAs/tools comparison and Roadprint functionality.

5.3.1 Expansion of LCA scope

The current scope of Roadprint only covers pavement construction. The scope can be incrementally extended to whole roadway projects, including bridges and tunnels.

More unit processes of construction could be added to the scope, such as saw operation, joint sealing, diamond grinding, crack, seat and overlay (CSOL), and dowel bar retrofit.

Work zone delays cause GHG emissions and increase user costs. By combining traffic data with work zone arrangements and traffic control arrangements, the environmental impacts associated with work zone traffic delays could be further simulated.

Some processes, such as heat islands and carbonation, can be included in the scope to evaluate the impacts from use phase (Santero, 2009). The uncertainty from use phase, such as traffic volume prediction, pavement roughness's effect on fuel consumption for vehicle operation, also needs further investigation.

5.3.2 Data inventory enhancement

In the proposed data inventory, several unit processes can be replaced and supplemented to improve the LCA results.

Data with lower quality scores are cullet, HMA, and aggregate production. Among them, HMA production has the biggest impact on LCA results. Current data used for HMA production combine energy data from IVL (2001) and emissions data from AP-42 (EPA 1997). Data from a single and consistent measuring method could replace the current data and describe this unit process better.

There are processes with omitted data. An actual measurement of WMA mixing will be useful because presently it is just prorated using HMA plant data. Supplemental data are also needed on aggregate/cement substitutes, which are comprised mostly of recycled materials and by-products. They are currently modeled by Roadprint as zero processes (a process with zero inputs and outputs) in the inventory, which does not hold true in actual processes. For recycled materials and by-products, an allocation procedure can help to determine the appropriate portion that these materials actually account for.

5.3.3 Pavement LCAs and tools comparison

Six pavement standard designs and three full-scale projects were compared in this research. Comparing more cases and tools would make the comparison more comprehensive, and help further understanding of the advantages and limitations of Roadprint.

5.3.4 Roadprint Functionality

The current functional unit only includes a single layer of surface course. Multilayer options and shoulder can be added to the functional unit and thus enable Roadprint to address pavement construction more completely.

The probabilistic analysis in Roadprint needs further development because it currently uses only the normal distribution function for probabilistic analysis. The normal distribution function may suffice for some variables. However, some other variables might be better described by other distribution functions. It would be useful to identify which distribution is suitable for each variable, and the results of probabilistic analysis would be more informative and valuable if users can select an appropriate distribution type for the variables. In addition, only parameter uncertainty was addressed using probabilistic analysis in this research. Other types of uncertainty in pavement LCA can be further investigated.

To better serve as a pavement LCA tool, usability testing could be conducted to make sure that user interface of Roadprint is friendly and intuitive. Furthermore, for better accessibility and to enable target users to access Roadprint more easily, it would be useful to adapt Roadprint from its current Excel format into an online tool.

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Appendix A: Pavement construction productivity analysis

The term “productivity” can be used as a performance index to evaluate the efficiency of operations, arrangement of resources, and work flow management in a paving project. Determining paving productivity is a task that invariably encounters a great deal of constraints, compromises, and drawbacks, with every job activity in the paving processes associated with individual or interactive effects. Therefore, productivity has to be predicted based on the available construction processes. In pavement LCAs, processes during life cycle phases need to be considered. This provides a good opportunity for LCA practitioners to conveniently assess the efficiency of their construction works, namely, their productivity.

A.1 Pavement productivity measurement and units

A.1.1 Hot mix asphalt (HMA) productivity

Productivity has several definitions and measuring approaches. From the project-level point of view, it is the ratio between the input (effort spent) and the output (quantity installed) (Ellis Jr. and Lee, 2006; Thomas and Zavrski 1999). Daily production is most often used as the unit of productivity. Schmitt et al. (1997) tried to apply techniques for measuring general construction productivity and unit costs to asphalt paving operations. Owing to their inherent complexity, these methods, which are derived from conventional construction concepts, are not easily accepted by the traditional pavement industry.

In HMA pavement construction, there are three common types of productivity units: weight by time, volume by unit time (cy/hr or m^3/hr), and area by unit time (lane-mile/day or square meters/hr). The volume-by-time unit is rarely used because weight units are more commonly accepted in the pavement industry. For area-type measuring, the lane-mile unit offers a rough measurement of a paving area, regardless of thickness and lane width. Although the use of the lane-mile/unit-time may not be as precise as using square meters/unit-time due to a range of lane widths from 9 to 12 ft (AASHTO, 2004), the most common lane width in highway design is 12 ft, making this measurement somewhat reasonable. Nevertheless, in terms of thickness, the validity of the area-type of unit is inconsistent. Choi and Minchin (2006) ignored the difference of thickness, asserting that each lift varies slightly (1.5 inch to 3 inch). The productivity unit in this study was m^2/hr. Another study measured the production rate by lane-meters in specific construction windows (55 hrs weekend closure and continuous closure) (Lee et al., 2002). It found that a thicker pavement profile decreases the production rate. Accordingly, the most acceptable type of units used to calculate HMA productivity is the “weight by time period” format, such as tons per hour or tons per day (tons/hr or tons/day) (NAPA, 1996; Jiang, 2007).

A.1.2 Portland cement concrete (PCC) productivity

Sometimes the distance per unit of time by the slip form paver is applied as the production rate. In addition, the measurement volume per unit cost is sometimes used. Some studies have even incorporated safety issues when evaluating a project’s performance (R.S. Means, 2004; Bryson et al., 2005; Bryson et al., 2007; Osmani et al., 1996). In practice, however, the paving productivity of PCC is mostly measured as volume per unit of time (m^3/day or yd^3/hr) (Roesler et al., 2000; Lee et al., 2000; Lee and Ibbs, 2005; Hassan and Gruber, 2008).

A.2 Construction activities of HMA/PCC pavements and productivity

The general construction activities of HMA paving are listed below in the sequence in which they occur (NAPA, 1996; Pavement Interactive, 2010):

1) Site preparation: this step includes demolition, sub-base grading, and sub-base compaction. The surface is ready to be paved after this step.

2) HMA production: this step mostly involves batch/drum plant operations. The available amount of HMA depends on the capacity and the efficiency of the plants.
3) HMA transport: this step includes HMA loading at the plant, the trucks' hauling time, and the unloading of the HMA at the site. The waiting time is occasionally added both at the plants and the sites.
4) Placement: this is the paver's operation. The efficiency depends on the capacity of the paver and the experience of the operator.
5) Compaction: this step includes breakdown rolling and finish rolling.

NAPA (1996) excluded the first step while calculating the production rate because the surface is supposed to be prepared before the arrival of the paving materials. Once the available HMA amount, the hauling time, the number of trucks, and the number of pavers and rollers are known, the production rate can be obtained. The efficiency of the site's preparation can be further integrated to obtain the paving productivity for HMA.

The general construction activities involved in PCC paving are outlined below, in their order of completion (Wright, 1996; NCPTC, 2006):

1) Site preparation: this step includes demolition, sub-base grading, and sub-base compaction. The surface is ready to be paved after this step.

2) Dowel/tie bars placement: dowel bars can be placed either manually or automatically by the PCC paver. The tie bars are only installed with the paver.
3) PCC production: this can be done either in a mixing truck or at central mixing plants.
4) PCC transport: this step includes PCC loading at the plant, the trucks' hauling time, and the unloading of the PCC at the site. The waiting time might be occasionally added both at the plants and the sites.
5) Placement: this step includes PCC spreading, consolidation, and screeding.
6) Finish: activities in this step include texturing, curing, and saw cutting.

As with HMA paving, the productivity of PCC can also be obtained once the amount of available PCC, the hauling time, and the number of trucks and pavers are known.

A.3 Issues in productivity in pavement construction

Operation synchronization in pavement production means that the production of the materials, their transport, and their placement are managed at the same pace, consequently minimizing the queue of ready materials or idle placement machineries. Once synchronization is achieved, the best productivity performance is expected (ACPA, 1995, NAPA, 1996).

In terms of the paving productivity of HMA, the following parameters are taken into account: the production of the asphalt mixture at the mixing plant, the materials' delivery rate from the plant to the construction site, the speed of the paving or the placement of the material, and the compaction speed (NAPA, 1996).

According to Choi and Minchin (2006), disruptions in asphalt paving operations can be categorized into management, work contents, and weather. Management can be broken down into: prerequisite work, out-of sequence work, rework, work conflict, work area, materials' shortage, and equipment breakdown. In their study, the loss of work hours caused by poor management ranged from 40% to 62%, by work content from 21% to 48%, and the effect of severe weather conditions from 6% to 17%. From this information, it is clear that workflow management is important in pavement construction productivity. However, this study did not specify how to ensure or improve the quality of workflow management.

Given the production rate of asphalt concrete, the major issue for paving productivity is the materials' delivery rate. The traffic flow at work zones and lane opening times at work zones influence the delivery rate of the materials, and, consequently, the productivity of the paving (Jiang, 2003;Nassar et al., 2003). A simulation model evaluated the impacts and interactions between number of trucks, lane opening time, hauling distance, and traffic volume. The results showed that the number of trucks and the lane opening time have more significant impacts on asphalt's pavement productivity than the other two factors (Nassar et al., 2003).

Statistical methodology was applied with project data from the Indiana Department of Transportation to compare the effects of weather conditions and construction sites on highway production rates (Jiang, 2007). The results showed that weather affected highway construction activities and those projects in rural areas achieved higher productivities due to reduced interference with traffic volume. In this research, the productivities of HMA and PCC were measured by ton/day and yd^2/day, respectively.

To avoid poor performance, pavement compaction needs to be completed while the pavements are at an appropriate temperature (Kennedy et al., 1984; Scherocman, 1996). Simulation tools, such as PaveCool and MultiCool, have been developed to estimate the available time for compaction before the pavements reach a cessation temperature (Chadboum et al. 1998; Timm et al., 2001). On the other hand, the best performance cannot be achieved if the paving materials are compacted while they are still fluid at very high temperatures. Therefore, if there is more than one lift to be paved, the cooling time will be a significant factor for paving productivity (Lee et. al., 2002).

HMA plants and PCC plants play a significant role in paving projects. To produce HMA, two types of plants are commonly used: drum or batch plants. For PCC, only batch plants are used. From the perspective of the production rate, drum plants are usually superior to batch ones (WSDOT, Pavement Guide 7.3). However, many factors affect mixing production. When discussing productive capacity, a plant is usually considered as a whole, and only its materials' (HMA or PCC) output is taken into account. Factors relating to internal equipment operation/productivity (such as excavator operation, hot/cold feed bin control, control of dryers) are usually integrated into "plant operation" to simplify the calculation of the production rate.

The availability of construction equipment and the workforce can affect working efficiency. The capacity and the number of pavers and rollers are usually proposed by contractors on the basis of their equipment to hand, and as approved by agencies. For trucks, ready mix is inferior to end dump (by load/unload rate and loading capacity) in terms of productivity (Roesler et al., 2000). While using the same set of equipment, the skills and the experience of the crew could affect productivity. Furthermore, for a single project, there is a learning curve, such that workers become more proficient and experienced by repeating similar jobs under the same, or almost the same, working conditions (weather, space, light) (Thomas et al., 1986; Lee et al., 2004; Hassanein and Moselhi, 2004).

It is not necessarily true that more construction resources result in better operating efficiency. A study that applied simulating tools, STROBOSCOPE and EZStrobe, showed that superfluous equipment and manpower would result in longer idle time and yield higher costs (Hassan and Gruber, 2008). This study acknowledged the limitations of the simulation: site conditions, capacities of the equipment, and the design of the construction operations need to be modified for every individual project.

Dowel bars are frequently used in PCC pavement. Dowel bars can be placed manually (arranged in dowel basket) before concrete is poured or by using dowel bar inserters (DBIs) during paving. DBIs can save manpower and time when installing dowel baskets, but whether DBIs are superior to dowel baskets in terms of the alignment and positioning of dowel bars remains a matter of debate (Hoegh and Khazanovich, 2009; FHWA, 2005). One thing that is sure is that a time window for dowel bar placement must be added into paving activities when dowel bars are used in PCC pavement.

For high-traffic volume roads, such as interstate highways, the strategy of lane closure for adequate working space could have significant effects. Previous studies (Lee et al., 2000, 2002, 2005) compared the advantages and disadvantages of the following closure schemes:

1) Night-time closure: 7 hours or 10 hours
2) Weekend closure: 55 hours
3) Weekday closure (Tuesday to Thursday): 72 hours
4) Continuous closure/continuous operation
5) Continuous closure with daytime only operation: one 10-hour shift or two 8-hour shifts.

In general, when longer closure windows were chosen, less time was spent on repeated mobilization/demobilization. Consequently, a higher production rate was achieved.

Using a precast concrete deck can accelerate highway construction by saving pouring and curing time, consequently, reducing user delays and raising productivity. This technology especially benefits paving jobs in heavy traffic areas, where long closures are not allowed. Current concerns with this application include an increase in the initial costs, lack of experience, demand for special equipment, lift-off of decks, and the strength of the joint structure (Merritt et al., 2001; AASHTO, 2008; Bull and Woodford, 1997).

The string-line technique has been used as a vertical and horizontal reference for concrete paving for decades. However, it has its limits and drawbacks, for example, a chord effect and time-intensive stacking of string lines. Global positioning systems (GPS) have been applied to guide slip-form pavers to provide adequate pavement depth and elevations and to reduce the time and cost associated with staking string lines (Rasmussen et al., 2004; NCPTC, 2004; Cable et al., 2009).

A simulation model called the Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) has been developed to facilitate highway rehabilitation planning. To simulate the productivity of pavement construction and rehabilitation, the input variables include the pavement's design and materials, resource constraints, and lane closure schemes (Lee et al., 2000). STROBOSCOPE, simulation software designed for construction operations, has also been applied to simulate paving operations. The simulation enables decision makers to evaluate different scenarios of resource arrangements in advance, thereby potentially saving time and costs (Hassan and Gruber, 2008).

A.4 Productivity calculation

To simulate the productivity of pavement construction and simplify the calculation, five assumptions and five exclusions are made. These assumptions are: (1) the conditions for construction are insignificant so they can be ignored. These conditions include weather, accessibility to sites, working space, lighting, etc.; (2) the traffic from the material suppliers to the site is always free flow, so no traffic delay will take place during construction; (3) there is no change in the paver's capacity when paving with different mixing deigns; (4) plants, trucks, and equipment always perform consistently; (5) there are no problems accessing the construction site, and the traffic flows freely to and from the plants.

Exclusions are: (1) the effects of crew size, their experience, and the learning curve; (2) the precast technique; (3) the time spent on dowel bar installation; (4) the effects of lane-closure scenarios; (5) the temperature and the curing time effects on the pavement's performance; (6) the dowel/tie bar installation, which has no impact on the paving productivity. Thus, the model considers the production of these steel bars, but excludes their installation.

Based on the construction activities and the assumptions and exclusions, productivity can be considered in terms of three operating factors: the production rate of the materials' mixing plants, the materials' hauling rate, and the materials' placement rate. For HMA pavements, the compaction rate also needs to be taken into account. Each factor is described in detail below.

The production rate is related to the operation and the capacity of the plants. The plant's operation includes aggregate heating, material conveyance, and storage. There are some factors that influence the operation, such as weather and communication (NAPA, 1996). For the sake of simplification, the operating processes are all integrated with capacity into one HMA or PCC "production rate." Another assumption is that the person calculating the productivity is aware of the factors that influence the plant's operation and can estimate the production rate based on those factors. Therefore, the plant's capacity can be simply viewed as the only index for the production rate. If sharing the plant with other projects, the designated supply rate is used instead of capacity.

The hauling rate is related to the transport distance, the available number of trucks, the capacity of the trucks, the load/unload time, and the waiting time at the plant/site (Nassar et al., 2003; Hassan and Gruber, 2008). Typically, the load/unload time is less than 5 minutes. In a good practice, the waiting time at the plant/site should not be longer than 5 minutes. Therefore, a bold assumption is made here: the hauling rate is only related to the transport distance and the capacity and the number of trucks.

The materials' placement rate is related to the amount of equipment and the equipment's capacity and efficiency. The equipment includes pavers, rollers for HMA, and spreaders for PCC pavement (NAPA, 1996; Hassan and Gruber, 2008). It is assumed that the crew is always available to operate this equipment during the paving process; therefore, the placement rate is determined and calculated by the critical capacity of this equipment.

Based on the aforementioned assumptions, exclusions, and discussion, the pavement's productivity can be calculated by 1) the plant's production rate, 2) the number and the capacity of the trucks, 3) the transport distance, 4) the amount of equipment, 5) capacity, and 6) the efficiency of the equipment.

A.5 Conclusions

The goals to be met in order to plan and arrange resources for pavement construction in advance are to: (1) optimize the available resources and the operating schedule, (2) identify suitable equipment considering the condition of the sites and other constraints, and (3) complete the projects at the lowest cost and within a targeted time frame (Moselhi and Alshibani, 2007). In essence, all efforts must be focused on optimizing the productivity of paving operations.

In this research, ton/hr and CY/hr were used as the default unit of productivity for HMA and PCC, respectively. Other measurements, such as area or day, would lead to confusion resulting from ambiguous units. For example, how many hours should be defined as a day? The answer could be 8 hours or 12. What is the total volume of this area of pavement? The answer not only depends on area of pavement, but also on its thickness. The use of specific weight/volume and time units enables users to convert to any other unit with which they are familiar. The volume can be then calculated if density information is available, and vice versa.

There are six required inputs for calculating paving productivity: (1) the plant's supply rate, (2) the number of trucks, (3) the capacity of the trucks, (4) the hauling distance, (5) the amount of equipment, and (6) the capacity/efficiency of the equipment. According to the reviewed LCA literature, the number of trucks, the amount of equipment, and the delivery distance are necessary inputs to implement a pavement LCA. Therefore, if the production rates of the mixing plants, the truck's capacity, and the capacities of the chosen equipment are added to the model, productivity can be calculated as a by-product of the pavement LCA.

Appendix B Pavement LCA Checklist and Roadprint Compliance

This "Pavement LCA Checklist" is part of the *UCPRC Pavement LCA Guideline*. It has been developed to help pavement life cycle practitioners prepare and organize essential information before conducting an analysis. It can also be used by LCA reviewers to identify differences among the basic elements of an LCA (such as system boundary or data source) and among different studies. It was prepared by the UCPRC LCA Research Team and was reviewed at the Pavement LCA Workshop held in Davis, California, in May 2010, with review comments included in the version shown here.

1 Goal and Scope Definition

1.1 Goal Definition

Study level (Choose one): ☐ Network level
☒ Project level

LCA type (Choose one): ☒ Single stand-alone LCA
☒ Comparative LCA

If "Comparative LCA" is selected, state the components that are assumed to be the same across systems:

1.2 Functional Unit

1.2.1 Physical dimension

Lane length: 1.609 km

Suggested: Max 100 km; Min 0.5 km

Lane width: 4 m
Number of lanes:
Including shoulder: ☐

If lane length, width, and number are not applicable, use total area: _____ m^2

Such as parking lots, airports, or intersections.

1.2.2 Performance requirements

Functional design life: _____ years
Truck traffic (AADT):
Climate:
Subgrade type:
Criteria for functional performance: _____ , _____ ,

1.3 Analysis Period

Method used to determine analysis period:

Analysis period: 50 years

1.4 Life Cycle Inventory

1.4.1 Primary energy: ☒
Clearly distinguish between feedstock energy and combusted energy: ☒
1.4.2 Greenhouse gases ☒
CO_2: ☒ CH_4: ☒
N_2O: ☒ Other:
1.4.3 Material flows ☒
1.4.4 Air pollutants
O_3: ☐ PM_{10}: ☒
$PM_{2.5}$: ☒ SO_2: ☒

CO: ☒
Volatile organic compounds: ☒
Others: SO_x NO_x ________, ________.
Lead: ☐
NO_X: ☒

1.4.5 Water pollutants ☐
1.4.6 Solid waste flows ☐
1.4.7 Other inventory categories ________, ________.

1.5 Pavement Structure Design and Life Cycle Phases

1.5.1 Pavement structure design (for each system)
Surface: ☒
Base or subbase: ☒
Subgrade: ☐
Shoulder: ☐
Drainage: ☐
Roadway lighting: ☐

1.5.2 Material Production Phase
Raw material #1 [List each of them]:
Material production: ☒
Feedstock energy: ☒
Transport of materials to site: ☒
1.5.2.1 *Engineered material*
Mixing in plant (HMA or PCC): ☒

1.5.3 Construction Phase and Maintenance and Rehabilitation Phase
Transport of materials to site: ☒
Transport from/to plant: ☒
Transport of recycled material: ☒
Equipment usage: ☒
Water use: ☐
Work zone traffic congestion: ☐
Vehicle technology change: ☐
Traffic growth: ☐
Lighting energy, if at night: ☐
Movement of equipment: ☐
Temporary infrastructure: ☐
Equipment manufacturing: ☐
Factory or plant construction: ☐

1.5.4 Use Phase
1.5.4.1 *Vehicle operation*
Impact to fuel economy from roughness: ☐
Damage to vehicle: ☐
Traffic growth: ☐
Change in vehicle technology: ☐
Damage to freight: ☐
Vehicle tire wear: ☐
1.5.4.2 *Heat island* ☐
1.5.4.3 *Non-GHG climate change mechanism* ☐
1.5.4.4 *Water pollution from runoff* ☐
1.5.4.5 *Roadway lighting* ☐
1.5.4.6 *Carbonation* ☐

1.5.5 End-of-Life Phase
1.5.5.1 *Recycling* ☒
Allocation: ☐

1.5.5.2 *Landfill*

Hauling of materials: ☐

Long-term water pollution: ☐

1.6 Impact Assessment

1.6.1 Global Warming

Global warming potential (GWP): ☒

Source : ☐ IPCC TAR
☐ IPCC AR4
☒ Other FRED

Time horizon (e.g. 100-yr, 20-year, etc.):

1.6.2 Other impact categories (List one by one.)

Impact category indicator: Acidification, Photochemical Smog, Eutrophication, Human Health

Source for calculation: FRED; TRACI

1.7 Sensitivity Analysis

1.7.1 Variables

Variables that are used to perform sensitivity analysis: ________, ________, ________, ________, ________,

2 Models and Data Sources

2.1 Material Production

2.1.1 Material LCI (List all the LCI sources)

LCI source #[1,2,…,n] name:

Type: ☒ LCI Tool (refers to database from company or research organizations)
☐ LCI Study (refers to publish journal paper or study report)

Meet ISO standard? ☒

Data quality evaluation: ☒

Statistical analysis: ☐

2.2 Construction

2.2.1 Maintenance and rehabilitation schedule

Determined from:

2.2.2 Equipment use ☐

Construction schedule analysis: ☐ Data source: Model:

Equipment emission: ☒ Data source: Model: NONROAD

Equipment fuel use: ☒ Data source: Model: NONROAD

Truck emission: ☒ Data source: Model: GREET 1.7

Truck fuel use: ☒ Data source: Model: GREET 1.7

2.2.3 Construction-related traffic ☐

Work zone traffic analysis: ☐ Data source: Model:

Traffic network analysis: ☐ Data source: Model:

Additional emission: ☐ Data source:

		Model:
Additional fuel use:	☐	Data source: Model:

2.3 Use

2.3.1 Vehicle operation Pavement performance model:	☐	Data source:
2.3.1.1 Impact to fuel economy Pavement – fuel use model:	☐	Data source:
2.3.1.2 Damage to vehicle Pavement – vehicle model:	☐	Data source:
2.3.1.3 Damage to freight Pavement – freight model:	☐	Data source:
2.3.1.4 Vehicle tire wear Pavement – tire model:	☐	Data source:
2.3.2 Urban heat island		
2.3.2.1 Albedo effect	☐	
Pavement aging – albedo model:		Data source:
Albedo – heat island model:		Data source:
Heat island – energy consumption relationship:		Data source:
2.3.2.2 Evaporative cooling	☐	
Evaporation – heat island relationship:		Data source:
Heat island – energy consumption relationship:		Data source:
2.3.3 Non-GHG climate change effects		
2.3.3.1 Albedo – radiative forcing	☐	
Albedo – radiative forcing model:		Data source:
Radiative forcing – GWP relationship:		Data source:
2.3.4 Leachate Pollutant transport model:	☐	Data source:
2.3.5 Carbonation Carbonation model:	☐	Data source:
2.3.6 Roadway lighting Electricity use model:	☐	Data source:

2.4 End-of-Life

2.4.1 Recycling Method used to allocate input and output:	☒	
2.4.2 Landfill	☐	
2.4.2.1 *Truck use*		
Truck emission:	☐	Data source: Model:
Truck fuel use:	☐	Data source: Model:

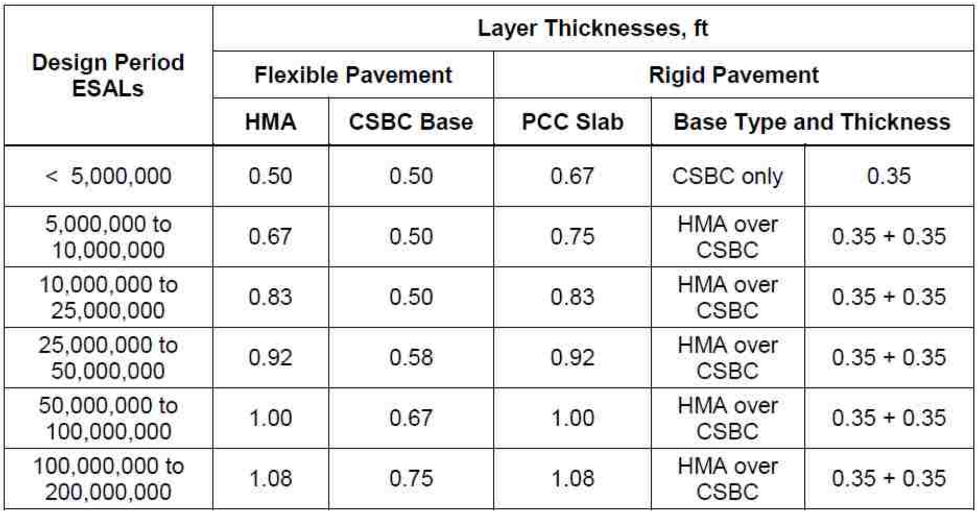
Appendix C: Roadprint Assessment – Standard Pavement Designs

Six standard pavement designs, two from WSDOT and four from Spain, were evaluated by Roadprint. There are four HMA pavements and two PCC pavement in these designs. The functional unit is set as “a one lane-mile (one mile long and 12 feet wide) pavement”. The analyzed period is 50 years.

C.1 Pavement Structure

Six pavement standard designs are selected to test ROADPRINT. Table C1 shows the flexible and rigid pavement designs in WSDOT Pavement Policy (WSDOT 2011). This study picked the flexible and rigid pavement structures which are designed for 25 to 50 million ESALs (WA-HMA and WA-PCC hereafter).

Table C.1 Flexible and rigid pavement layer thickness for new constructed pavements (WSDOT, 2011)



Design Period ESALs	Layer Thicknesses, ft				
	Flexible Pavement		Rigid Pavement		
	HMA	CSBC Base	PCC Slab	Base Type and Thickness	
< 5,000,000	0.50	0.50	0.67	CSBC only	0.35
5,000,000 to 10,000,000	0.67	0.50	0.75	HMA over CSBC	0.35 + 0.35
10,000,000 to 25,000,000	0.83	0.50	0.83	HMA over CSBC	0.35 + 0.35
25,000,000 to 50,000,000	0.92	0.58	0.92	HMA over CSBC	0.35 + 0.35
50,000,000 to 100,000,000	1.00	0.67	1.00	HMA over CSBC	0.35 + 0.35
100,000,000 to 200,000,000	1.08	0.75	1.08	HMA over CSBC	0.35 + 0.35

The Spanish designs are shared by a Spanish research assistant who visited University of Washington in 2011. Her research topics are associated with the Spanish pavement LCA tool, OASIS. Since this research involves OASIS, four typical Spanish highway structural designs are also included in this research (S1, S2, S3 and S4 hereafter). The performance criterion for the designs is 5,000 heavy-truck trips per day. The percentage of truck in total traffic volume is unknown.

The structures of all six pavement designs are shown in Table C2. Maintenance schedule for all cases are assumed based on general practice.

Table C.2 Pavement structure design and maintenance schedule

Design	Surface	Base	Maintenance
WA-HMA	HMA, 11 in	CSBC*, 7 in	Remove/add HMA 1.8 in, 3 times
WA-PCC	Reinforce concrete, 11 in	HMA 4.2 in+ CSBC 4.2 in	None
S 1	HMA, 10 in	Soil cement, 12 in	Add HMA 1.625 in, 4 times
S 2	HMA, 14 in	Ballast, 10 in	Add HMA 2.2, 4 times
S 3	HMA, 8 in	Soil cement 10 in + Gravel cement 8.8 in	Add HMA 1.625 in, 4 times
S 4	Reinforce concrete, 10 in	Lean concrete, 6 in	None

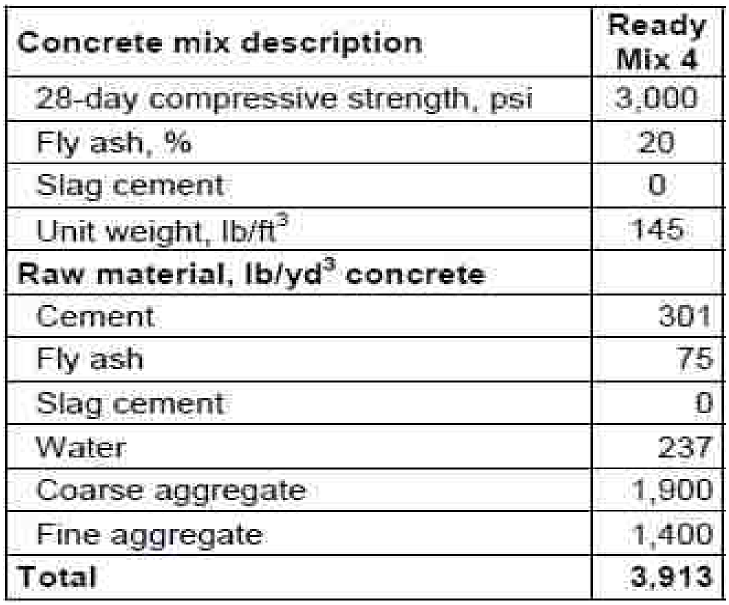
*CSBC: Crushed surfacing base course

These standard designs are only structural designs. Hence other necessary parameters are estimated based on general practice and reasonable assumptions. These estimated parameters in terms of material, transportation, and equipment are described in following sections.

C.2 Materials

HMA mix design: the mix design for HMA mixture is set at 5% bitumen, 85% crushed rock and 10% sand. No WMA/RAP is used any cases. Feedstock energy of the bitumen is 40.2 MJ/kg according to IPCC (2006). Ready-mix concrete with 28-day compress strength of 3000 psi is used for PCC pavement. The concrete mix design is shown in Table C3.

Table C.3 Ready mix concrete mix design



Concrete mix description	**Ready Mix 4**
28-day compressive strength, psi	3,000
Fly ash, %	20
Slag cement	0
Unit weight, lb/ft^3	145
Raw material, lb/yd^3 concrete	
Cement	301
Fly ash	75
Slag cement	0
Water	237
Coarse aggregate	1,900
Fine aggregate	1,400
Total	**3,913**

C.3 Transportation

Heavy-duty trucks implement all transportation except for bitumen is transported by medium-heavy truck. The transporting distance is 31.075 miles (50 km) for all materials.

C.4 Equipment

Users have to specify different number of equipment, engine size, working time, and efficiency factor in Roadprint. Equipment used in WA-HMA is shown in Table C4. S1 to S3 used same set of equipment, except that no milling machine was involved. WA-PCC and S4 use the same equipment, as shown in Table C5. Other equipment assumptions: the moldboard width of the grader is 12 feet, and the sub-base grading requires a 24-inch overlap between each path. Two passes are needed. The roller drum width is 6.6 feet. A 6-inch path overlap and 3 passes are required to meet the desired density. Assume four lifts for HMA surface paving in all HMA cases.

Table C.4 Equipment list for HMA pavement

Equipment		Amount	Engine Size (HP)	Performance Index	Working Time %	Efficiency Factor
Embankment	Grader	2	175	15 (ft/min)	50	0.85
	Excavator 1	2	175	N/A	20	0.85
	Excavator 2	1	50	N/A	5	0.85
	Backhoe	1	100	N/A	20	0.85
	Loader	1	175	N/A	10	0.85
Initial	HMA Paver 1	1	175	15 (ft/min)	100	0.85
	HMA Paver 2	1	100	15 (ft/min)	5	0.85
	MTV	1	300	15 (ft/min)	100	N/A
	Breakdown Roller 1	2	175	15 (ft/min)	100	0.85
	Breakdown Roller 2	1	175	15 (ft/min)	5	0.85
	Finish Roller	1	100	15 (ft/min)	100	0.85
	Milling Machine	1	750	300 (ton/hr)	100	0.85
Maintenance	HMA Paver 1	1	175	15 (ft/min)	100	0.85
	HMA Paver 2	1	100	15 (ft/min)	5	0.85
	MTV	1	300	15 (ft/min)	100	N/A
	Breakdown Roller 1	2	175	15 (ft/min)	100	0.85
	Breakdown Roller 2	1	175	15 (ft/min)	5	0.85
	Finish Roller	1	100	15 (ft/min)	100	0.85
	Milling Machine	1	750	300 (ton/hr)	100	0.85

Table C.5 Equipment list for PCC pavement

Equipment		Amount	Engine Size (HP)	Performance Index	Working Time	Efficiency Factor
Embankment	Grader	2	175	15 (ft/min)	50	0.85
	Excavator 1	1	175	N/A	20	0.85
	Excavator 2	1	50	N/A	5	0.85
	Backhoe	1	100	N/A	20	0.85
	Loader	1	175	N/A	10	0.85
Initial	PCC Spreader	1	300	4 (ft/min)	100	0.8
	PCC Spreader	1	300	4 (ft/min)	100	0.8
	PCC Paver 1	1	600	4 (ft/min)	100	N/A
	HMA Paver 1	1	175	15 (ft/min)	100	0.85
	HMA Paver 2	1	100	15 (ft/min)	5	0.85
	MTV	1	300	15 (ft/min)	100	N/A
	Breakdown Roller 1	2	175	15 (ft/min)	100	0.85
	Breakdown Roller 2	1	175	15 (ft/min)	5	0.85
	Finish Roller	1	100	15 (ft/min)	100	0.85
	Milling Machine	1	750	300 (ton/hr)	100	0.85

C.5 Productivity simulation

The jobsite is 31.075 (km) mile away from the HMA/PCC mixing plants. Since these cases are just pavement designs, some necessary parameters for simulating productivity are estimated based on reasonable assumptions. Like equipment, HMA designs and PCC design use different sets of parameters. These assumed parameters are shown in Table C6. The results of productivity simulation are shown in Table C7.

Table C.6 Assumed parameters for productivity simulation

	HMA	PCC
HMA Plant supply rate (ton/hr)	200	200
PCC Plant supply rate (ton/hr)	-	325
Truck capacity (ton)	20	20
Waiting time at plant (min)	10	10
Waiting time at site (min)	10	10
Truck travel speed (mi/hr)	50	50

Table C.7 Results of productivity simulation

	WA-A	WA-B	S1	S2	S3	S4
HMA Paving productivity (ton/hr)	152.12	58.08	138.29	129.07	110.63	-
PCC Paving productivity (ton/hr)	-	79.4	-	-	-	54.13
Truck needed for HMA paving	13	5	12	11	9	-
Truck needed for PCC paving	-	7	-	-	-	5

C.6 Lifecycle impact assessments results

This section shows the LCIA result of all six cases. Table C8 shows the complete LCIA results.

Table C.8 Tabular LCIA results

Phase		Energy Consumption		Global Warming Potential		Acidification		Photochemical Smog		Eutrophication		Human Health Criteria Air	
		Energy (GJ)		GWP(CO2 Mg-E)		Kg SO2		Kg NOx		Kg PO4		milli - DALYs/Kg	
Material Production	WA-HMA	5535	74.0%	251	62.4%	825	18.5%	799	48.6%	77	43.6%	28	34.4%
	WA-PCC	4598	79.6%	490	84.2%	1544	42.4%	1272	70.3%	155	71.1%	113	78.5%
	S-1	6871	76.6%	470	74.1%	1592	29.6%	1365	60.0%	149	58.0%	85	60.5%
	S-2	7711	75.1%	356	64.2%	1150	19.3%	1108	50.3%	107	45.3%	39	35.4%
	S-3	7189	76.9%	601	78.1%	2065	34.8%	1690	64.3%	193	63.5%	126	68.9%
	S-4	4014	83.8%	560	90.2%	1763	56.8%	1388	80.0%	176	80.6%	128	86.7%
Equipment	WA-HMA	544	7.3%	44	11.0%	235	5.3%	352	21.4%	41	22.9%	7	8.1%
	WA-PCC	379	6.6%	31	5.2%	168	4.6%	257	14.2%	29	13.4%	4	3.1%
	S-1	623	6.9%	51	8.0%	264	4.9%	394	17.3%	45	17.7%	7	5.2%
	S-2	676	6.6%	55	9.9%	288	4.8%	436	19.8%	50	21.0%	8	7.4%
	S-3	645	6.9%	53	6.9%	273	4.6%	407	15.5%	47	15.5%	8	4.2%
	S-4	261	5.5%	22	3.5%	119	3.8%	169	9.7%	21	9.5%	3	2.0%
Transportation	WA-HMA	1400	18.7%	107	26.6%	3399	76.2%	493	30.0%	59	33.5%	47	57.5%
	WA-PCC	800	13.8%	61	10.5%	1931	53.0%	281	15.5%	34	15.6%	26	18.4%
	S-1	1479	16.5%	113	17.8%	3529	65.5%	518	22.7%	62	24.3%	48	34.3%
	S-2	1880	18.3%	144	25.9%	4537	75.9%	660	29.9%	80	33.7%	62	57.2%
	S-3	1518	16.2%	116	15.1%	3590	60.6%	530	20.2%	64	21.0%	49	27.0%
	S-4	512	10.7%	39	6.3%	1221	39.4%	179	10.3%	22	9.9%	17	11.3%
Total	WA-HMA	7478		402		4460		1644		177		81	
	WA-PCC	5777		582		3644		1810		218		144	
	S-1	8973		634		5385		2276		257		141	
	S-2	10267		554		5975		2204		236		109	
	S-3	9353		770		5929		2627		304		183	
	S-4	4787		621		3104		1736		218		148	

C.7 Compare Roadprint with other pavement LCA tools

The six standard designs are also evaluated by OASIS, PaLATE v2.2, EIOLCA, and PE-2. Results from each tool are used to assess the capability of Roadprint. The material parameters, Roadprint equipment inputs and transportation assumptions are the same as in Section C.2 to C.4. Equipment inputs in PaLATE v2.2, OASIS, and PE-2 are listed in Table C9 to Table C11.

Table C9 Equipment inputs in PaLATE v2.2

	Equipment	Description
S1 S2 S3	Wheel Loader	160 hp
	Paver	200 hp
	Pneumatic Roller	100 hp
	Tandem Roller	125 hp
	Excavator	130 hp
	Asphalt Mixer	Fabric filter-controlled drum mix
S4	Wheel Loader	160 hp
	Excavator	130 hp
	Plant Mixer	200 hp electric concrete plant
	Slipform Paver	250 hp concrete slipform paver
	Texture Curing Machine	70 hp
WA-HMA	Wheel Loader	160 hp
	Paver	200 hp
	Pneumatic Roller	100 hp
	Tandem Roller	125 hp
	Milling Machine	875 hp
	Excavator	130 hp
	Asphalt Mixer	Fabric filter-controlled drum mix
WA-PCC	Wheel Loader	160 hp
	Slipform Paver	250 hp

	Equipment	Description
	Texture Curing Machine	70 hp
	Paver	200 hp
	Pneumatic Roller	100 hp
	Tandem Roller	125 hp
	Plant Mixer	200 hp electric concrete plant
	Asphalt Mixer	Fabric filter-controlled drum mix

Table C10 Equipment inputs in OASIS

Project	Equipment
S1 S2 S3 WA-HMA	Self-propelled vibratory roller, 12 - 14 t
	Road grader for HMA pavements
	Self-propelled vibratory roller for bitumen and concrete (pneumatic)
	Milling Machine
	Middle grader
S4 WA-PCC	Paver for concrete pavements
	Self-propelled vibratory roller, 12 - 14 t
	Road grader for HMA pavements
	Self-propelled vibratory roller for bitumen and concrete (pneumatic)
	Milling Machine
	Middle grader

Table C11 Equipment inputs in PE-2

Project	Equipment
S1 S2 S3 WA-HMA	Grader
	Excavator
	Backhoe
	Loader
	HMA Paver
	MTV
	Breakdown Roller
	Finish Roller
	Milling Machine
S4 WA-PCC	Grader
	Excavator
	Backhoe
	Loader
	HMA Paver
	MTV
	Breakdown Roller
	Finish Roller
	PCC Spreader
	PCC Paver
	Milling Machine

Appendix D: Roadprint assessment on full scale projects

In addition to the six standard designs, three projects are selected for the comparison: SR-240, US-97 and Keulo Drive. The goal is to further assess the dependability and discernibility of Roadprint on various circumstances in full scale pavement constructions. Sections D.1 to Section D.3 describe each project in terms of general information, material parameters, transportation parameters, and maintenance strategy. Section D.4 shows the equipment inputs for each project and tool.

D.1 Keolu Drive

Project descriptions: this project is composed of two sections: Wanaao Rd. to Akaakawa St. and Kalanianaole Hwy to Akahai Street, in Kailua, HI. The general scope is to mill 6 inch of existing HMA pavement (total 13188 yd^3) on a residential road, and then resurface with 2" asphalt concrete pavement (ACP) over 4" of asphalt concrete base (ACB). Total length is about 5 miles. The location is shown in Figure D1.

Materials: in initial construction, this project used 9,516 ton of ACP and 18,790 ton of ACB. The mix design of ACP is 5.5% bitumen, 94.5% crushed stone; the mix design for ACB is 5% bitumen, 10% cullet and 85% crushed stone. For maintenance, the mix design is the same with ACP, and total tonnage is 7913 tons.

Transportation: the transport distance of HMA, crushed stone, and RAP is 6 miles. Asphalt cement is originally supplied from a refinery in New Brunswick, Canada, shipped to a terminal at Kalaeloa Harbor and then trucked to the HMA plant. Transportation distance for the asphalt cement is set as the distance from the Kalaeloa Harbor terminal to the HMA plant, approximately 30 miles.

Maintenance: 2”ACP mill-and-fill in year 10, 20, 30, and 40.

Figure D1 Project map of Keolu Drive

D.2 US-97, Lava Butte - South Century Drive

Project descriptions: this project was located in central Oregon along US 97. This project increased the capacity by converting the existing two-lane highway into a four-lane (two in each direction) highway. Two inches of existing surface are removed before paving. Construction began in April 2009 and will be completed in Fall 2012. The location is shown in Figure D2.

Materials: US-97 used 96,600 tons of HMA and 113,000 tons of plant mix aggregate base. The HMA mix design is 6.16% bitumen, 20% RAP and 73.4% crushed stone. RAP is also used for 30% of total base material.

Transportation: the aggregate source is 4 miles away from the HMA plant, and bitumen supplier is 30 miles away from the HMA plant. Transportation distance for all other materials are assumed 30 mile.

Maintenance: the assumed maintenance schedule is to add 2 inch of HMA wearing course every 15 years.

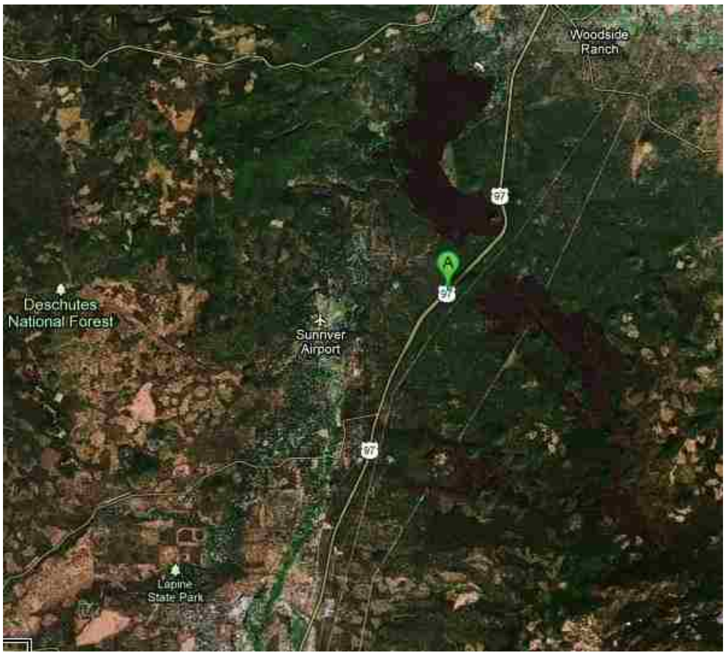


Figure D2 Location of project US-97

D.3 SR-240, I-182 to Columbia Center I/C

Project descriptions: this is a new constructed PCC project. It added additional lanes on SR-240 between Richland and Kennewick, Washington. Project began in May 2005 and completed in June 2007. The location is shown in Figure D3.

Materials: SR-240 used 65,090 tons of HMA, 39,830 cys of ready mix concrete, 185,690 tons of CSBC, and 68,100 pieces of dowel bar. This project used 4,500 psi ready mix concrete for PCC pavement. There is no information for HMA mix design, and it is assumed using 5% bitumen, 10% sand and85% crushed stone.

Transportation: this project used a temporary PCC plant only 0.5 miles away from the jobsite. The HMA mixing facility is 12 miles away to the job site. Other than that, there is no available data for material transportation. Transportation distance for other materials is assumed 50 km (31.075 mile).

Maintenance: no maintenance is scheduled for this project.

Figure D3 Location of project SR-240

D.4 Equipment

In Roadprint, Users have to specify different number of equipment, engine size, working time, and efficiency factor. However, there is no available information about equipment usage for these projects. Therefore equipment inputs in Raodprint are common estimation or reasonable assumption. The equipment inputs of SR-240, US-97 and Keolu Drive are shown in Table D1 to Table D3.

Table D1 Roadprint equipment inputs for SR-240

Equipment		Amount	Engine Size (HP)	Performance Index	Working Time %	Efficiency Factor
Embankment	Grader 1	2	175	15 (ft/min)	100	0.85
	Grader 2	1	75	15 (ft/min)	20	0.85
	Excavator 1	2	175	N/A	20	0.85
	Excavator 2	1	50	N/A	5	0.85
	Backhoe	1	100	N/A	20	0.85
	Loader	1	175	N/A	10	0.85
Initial	HMA Paver 1	1	175	15 (ft/min)	100	0.85
	HMA Paver 2	1	100	15 (ft/min)	5	0.85
	MTV	1	300	15 (ft/min)	100	N/A
	Breakdown Roller 1	2	175	15 (ft/min)	100	0.85
	Breakdown Roller 2	1	175	15 (ft/min)	5	0.85
	Finish Roller	1	100	15 (ft/min)	100	0.85
	PCC Spreader	1	300	4 (ft/min)	100	0.8
	PCC Spreader	1	300	4 (ft/min)	100	0.8
	PCC Paver 1	1	600	4 (ft/min)	100	N/A
Maint.	HMA Paver 1	1	175	15 (ft/min)	100	0.85
	MTV	1	300	15 (ft/min)	100	N/A
	Breakdown Roller 1	2	175	30 (ft/min)	100	0.85
	Finish Roller	1	100	30 (ft/min)	100	0.85
	Milling Machine	1	750	300 (ton/hr)	100	0.85

Table D2 Roadprint equipment inputs for project US-97

Equipment		Amount	Engine Size (HP)	Performance Index	Working Time %	Efficiency Factor
Embankment	Grader	2	175	15 (ft/min)	100	0.85
	Excavator 1	2	175	N/A	40	0.85
	Excavator 2	1	50	N/A	15	0.85
	Backhoe	1	100	N/A	60	0.85
	Loader	1	175	N/A	30	0.85
Initial	HMA Paver 1	1	175	15 (ft/min)	100	0.85
	HMA Paver 2	1	100	15 (ft/min)	5	0.85
	MTV	1	300	15 (ft/min)	100	N/A
	Breakdown Roller 1	2	175	15 (ft/min)	100	0.85
	Breakdown Roller 2	1	175	15 (ft/min)	5	0.85
	Finish Roller	1	100	15 (ft/min)	100	0.85
	Milling Machine	1	750	200 (ton/hr)	100	0.85
Maint.	HMA Paver 1	1	175	15 (ft/min)	100	0.85
	MTV	1	300	15 (ft/min)	100	N/A
	Breakdown Roller 1	2	175	15 (ft/min)	100	0.85
	Breakdown Roller 2	1	175	15 (ft/min)	5	0.85
	Finish Roller	1	100	15 (ft/min)	100	0.85

Table D3 Roadprint equipment inputs for project Keolu Drive

Equipment		Amount	Engine Size (HP)	Performance Index	Working Time %	Efficiency Factor
Embankment	Excavator 1	2	175	N/A	40	0.85
	Excavator 2	1	50	N/A	20	0.85
	Backhoe	1	100	N/A	40	0.85
	Loader	1	175	N/A	40	0.85
Initial	HMA Paver 1	1	175	15 (ft/min)	100	0.85
	HMA Paver 2	1	100	15 (ft/min)	5	0.85
	MTV	1	300	15 (ft/min)	100	N/A
	Breakdown Roller 1	2	175	15 (ft/min)	100	0.85
	Breakdown Roller 2	1	175	15 (ft/min)	5	0.85
	Finish Roller	1	100	15 (ft/min)	100	0.85
	Milling Machine	1	750	200 (ton/hr)	100	0.85
Maint.	HMA Paver 1	1	175	15 (ft/min)	100	0.85
	MTV	1	300	15 (ft/min)	100	N/A
	Breakdown Roller 1	2	175	15 (ft/min)	100	0.85
	Breakdown Roller 2	1	175	15 (ft/min)	5	0.85
	Finish Roller	1	100	15 (ft/min)	100	0.85
	Milling Machine	1	750	100 (ton/hr)	100	0.85

In PaLATE v2.2, users only select equipment models from built-in lists for different equipment. The environmental impacts are calculated only based on the selected equipment modes.

In OASIS, each unit of material has its corresponding set of equipment. Users are not able to modify the equipment inputs. Equipment-related environmental impacts are hence proportional to the amount of materials.

In PE-2, users are allowed to select equipment model and the corresponding operating hours. GHG emissions are calculated based on equipment type, mode and operating hours.

EIOLCA model does not contain any information of construction equipment.

Again the equipment inputs in these tools just are estimations and assumptions because there is no available information. Table D4 to Table D6 show selected equipment for PaLATE v2.2, OASIS and PE-2.

Table D4 Equipment inputs for PaLATE v 2.2

Project	Equipment	Description
Keolu Drive	Wheel Loader	160 hp
	HMA Paver	200 hp
	Pneumatic Roller	100 hp
	Tandem Roller	125 hp
	Milling Machine	875 hp
	Excavator	130 hp
	Vibratory soil compactor	150 hp
	Glass recycling	10 hp electric glass pulverizer
	Asphalt Mixer	Fabric filter-controlled drum mix
US 97	Wheel Loader	160 hp
	HMA Paver	200 hp
	Pneumatic Roller	100 hp
	Tandem Roller	125 hp
	Milling Machine	875 hp
	Excavator	130 hp
	Vibratory soil compactor	150 hp
	Asphalt Mixer	Fabric filter-controlled drum mix
SR-240	Excavator	130 hp
	Vibratory soil compactor	150 hp
	Wheel Loader	160 hp
	PCC Slipform paver	250 hp
	Texture Curing Machine	70 hp
	HMA Paver	200 hp
	Pneumatic Roller	100 hp
	Tandem Roller	125 hp
	Plant Mixer	200 hp electric concrete plant
	Asphalt Mixer	Fabric filter-controlled drum mix

Table D5 Equipment inputs for OASIS

Project	Equipment
Keolu Drive	Self-propelled vibratory roller, 12 - 14 t
	Road grader for HMA pavements
	Self-propelled vibratory roller for bitumen and concrete (pneumatic)
	Milling Machine
	Middle grader
US 97	Self-propelled vibratory roller, 12 - 14 t
	Road grader for HMA pavements
	Self-propelled vibratory roller for bitumen and concrete (pneumatic)
	Milling Machine
	Middle grader
SR-240	Paver for concrete pavements
	Self-propelled vibratory roller, 12 - 14 t
	Road grader for HMA pavements
	Self-propelled vibratory roller for bitumen and concrete (pneumatic)
	Milling Machine
	Middle grader

Table D6 Equipment inputs for PE-2

Project	Equipment
Keolu Drive & US-97	Grader
	Excavator
	Backhoe
	Loader
	HMA Paver
	MTV
	Breakdown Roller
	Finish Roller
	Milling Machine
SR-240	Grader
	Excavator
	Backhoe
	Loader
	HMA Paver
	MTV
	Breakdown Roller
	Finish Roller
	PCC Spreader
	PCC Paver
	Milling Machine