Life Cycle Assessment of Concrete Pavements: Impacts and Opportunities

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ABSTRACT

The concrete pavement network in the United States plays a crucial role in the economy by enabling the transport of people and goods, but it also leads to resource consumption and environmental impacts. This thesis is fundamentally motivated to reduce the impact that concrete pavements have on climate change. The principal methodology that is used is life cycle assessment (LCA), which comprehensively includes all five primary phases of the life cycle: materials extraction and production, pavement construction, pavement rehabilitation, the use phase, and end-of-life recycling and disposal. This work informs the reduction of life cycle greenhouse gases (GHGs) through a three-pronged approach to: 1) comprehensively quantify GHG emissions for structures representing all primary pavement types in the US, 2) establishes a benchmark for GHG emissions from all concrete pavements in the US constructed annually, and 3) identifies five reduction strategies and measures the GHG reduction that is obtainable through these strategies, both at the project-level for different road classes and at the national level. This provides a portfolio of GHG reduction options to national and regional policymakers, transportation agencies, and pavement engineers.

Thesis supervisor: John Ochsendorf

Title: Associate Professor
I would first like to thank my advisor, Professor John Ochsendorf, for being the catalyst that allowed me to achieve all that I wanted to and much more in two years. Watching John’s ability to inspire, be diplomatic, and guide our group with unwavering patience has enriched me not only academically, but also professionally. Secondly I would like to thank Doctor Nicholas Santero for his inspirational work before meeting him, and his generous attitude of teamwork while working with him. His exhilaration and curiosity has, and will surely continue to, bring new energy to this field and beyond. Thank you also to my colleagues Mehdi Akbarian and Sahil Sahni, and to Professor Timothy Gutowski. I am also grateful to the Concrete Sustainability Hub at MIT for supporting this research. A big thank you also goes out to James W. Mack at CEMEX for continuous advice from his experienced perspective on pavement design engineering. Mr. Mack contributed significantly to the pavement designs and their roughness predictions found in this thesis. Thank you also to Peter Canepa and Laura Mar at PE Americas for their software implementation support.
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SECTION I: INTRODUCTION

CHAPTER 1: PROBLEM STATEMENT AND BACKGROUND

1.1 INTRODUCTION

This chapter sets the foundation for the analysis conducted in this thesis by motivating the need to quantify and reduce the life cycle greenhouse gas (GHG) emissions of concrete pavements in the United States. This motivation leads to a three-fold approach to solve this problem. Finally, the prior research in this domain demonstrates that these questions remain unanswered and would benefit both the research community and transportation policymakers that need to meet GHG reduction targets.

1.2 PROBLEM STATEMENT

The road transportation system in the US plays an integral role in enabling economic activity by providing people with the mobility to access jobs, recreation, and other people, and allowing economic markets to exchange goods and services. While the infrastructure for this system facilitates productivity, the production of materials for construction, maintenance, and rehabilitation of the US roadway system are responsible for substantial energy and resource consumption, as well as pollution of the environment that results from those consumptive activities.

The two primary types of pavements are concrete and asphalt pavements, but the present analysis is limited to concrete pavements alone. The extent of pavements in the United States that contain a significant layer of concrete (which includes both concrete and composite pavements) is
approximately 254,000 kilometers (Federal Highway Administration 2008). This is enough to wrap around the circumference of the earth at the equator over 6 times.

In the year 1996, about 26% of all concrete end-use in the US went into highways and roads, or roughly 226 million metric tons (Low 2005). For a sense of scale, in the same year this is equivalent to about one-quarter the mass of crude oil and petroleum products consumed in the US (EIA 2010), and about equal to the quantity of municipal solid waste generated in the US (EPA 2008). There are significant impacts on global climate change associated with producing such a vast quantity of materials. This is especially true when considering the greenhouse gases (GHGs) that are emitted by cement plants in order to produce common concrete paving materials. The EPA ranks “Cement Production” as the fourth largest industrial sources of carbon dioxide in the US, which is a primary concrete pavement material (EPA 2009).

Rivaling the environmental impact of producing these materials are the significant greenhouse gases released during the operation of pavements by vehicles. Road transport contributed the most greenhouse gases of any transport mode in 2007, accounting for 83% of emissions from the transportation sector, and 27% of all emissions in the US (EPA 2009). Pavement construction plays a role in the ride quality and fuel efficiency of the vehicle during the pavement’s operation, which relates to traffic, paving material properties, how well the road is maintained, and other factors. In addition, fuel efficiency can be increased through improved pavement design, construction and maintenance. There are also other important environmental impacts during the operation (or use phase) of pavements, including pavement lighting, traffic delay from construction and rehabilitation, and the effects of pavement albedo and carbonation (Santero and Horvath 2009).
Can society “do more with less” by moving towards more eco-efficient consumption patterns? Environmental regulations are mounting to mandate greenhouse gas reductions, such as California’s Assembly Bill 32 “Global Warming Solutions Act,” which must adopt discrete actions to achieve technologically feasible and cost-effective greenhouse gas reductions (CARB 2011). The market mechanisms are stipulated to be legally enforceable by January 1, 2012, so the urgency to reduce GHG in California is greater than ever. Given the integral role that pavements play in our society, as well as the large environmental impact from their construction and from their use, the life cycle assessment (LCA) methodology offers a lens for identifying opportunities to make this system more eco-efficient, serving the needs of society and the economy, while minimizing negative environmental harms. The fundamental objective of this thesis is to identify opportunities to reduce the impacts on global warming that are due to the concrete pavement infrastructure in the US. This is accomplished through a three-pronged LCA approach:

1) Quantify life cycle greenhouse gas emissions in a systematic and comprehensive way so as to capture a) the primary functional classes of concrete pavements and b) all relevant life cycle phases. This approach allows for the first time a comparative understanding of how the overall GHG emissions differ according to the character of service of all primary pavement types, as well as how the contributions from the various life cycle components change across these functional types.

2) Benchmark life cycle GHG emissions of all concrete pavements that are constructed each year in the US. This establishes for the first time an estimate of the size of this problem, and
a clear benchmark of current emissions as a basis for measuring future annual emissions and reductions over time.

3) Identify opportunities for GHG reductions of concrete pavements, and quantify the GHG reduction on a project-level basis and a network-wide basis. This measures for the first time the potential of these strategies for different pavement types, which serves transportation agencies and construction contractors to prioritize reduction strategies for the different types at the project level. This also shows the reduction potential across the entire US concrete pavement network, that could be achieved by nationwide policy at the federal level.

The resulting information can be used to guide “green design” practices and respective policies within state and federal transportation agencies so as to enable an increasingly sustainable road transportation network. In the following section the prior relevant literature will be reviewed to demonstrate a need for the present line of inquiry.

1.3 BACKGROUND

1.3.1 The Life Cycle Assessment Methodology

There are a wealth of tools that have been used by the scientific and industrial community to quantify the environmental performance of pavements. Many of them focus on certain “green”
features that show measurable benefits, such as a pavement’s recyclability, water control and porosity, durability, noise control, reflective albedo, and carbonation, all of which draw on methods from a variety of scientific disciplines: hydrology, thermodynamics, hydrology, structural mechanics, etc. A few different systems have developed for combining these various concerns in order to evaluate pavements in a comprehensive manner, balance environmental costs and benefits, as well as include systemic impacts occurring in the entire value chain. The systems listed in Table 1.1 are all based on earning points for each of a variety of environmental, economic and social criteria as measures of the “triple bottom line” (Elkington 1997).

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Table 1.1 - Points-based systems for evaluating sustainability of pavements.

These evaluation systems no doubt have many merits, especially compared to a pavement that is designed and built without bearing in mind any environmental impact considerations. A common criticism, however, of points-based systems, is that the design focus is shifted from good design to obtaining credits, and that credits are not weighted to accurately reflect environmental impacts (Soderlund et al. 2008). One example is that GreenLITES awards three points for including a roundabout
or a special use lane, which are design additions that can improve traffic flow on busy roads. But this may provide a perverse incentive to use an exorbitant quantity of materials on a road with good anticipated traffic flow. The LEED accreditation system for buildings is often criticized for similar reasons, and when “…considered in a life cycle perspective LEED™ does not provide a consistent, organized structure for achievement of environmental goals” (Scheuer and Keoleian 2002). The arbitrary selection and weighting of evaluation criteria is one of the reasons why so many of these systems have developed, as there is no systematic method for the systems to converge on a best practice. Life cycle assessment, however, provides a scientifically-based methodology for selecting, quantifying, weighting, and normalizing environmental criteria. These criteria can include multiple environmental impacts, and the “life cycle” refers to the focus on systemic impacts. This methodology is therefore the preferred method for evaluating the environmental performance of pavements, and is described below.

Life cycle assessment is a method within the field of industrial ecology that can be generally applied to industrial systems. LCA comprehensively quantifies, and evaluates the material and energy flows of such a system. These materials and flows are inventoried throughout the “life cycle” of the product and/or service that comprises the system, including upstream (raw material extraction, processing, transportation, and construction), use (reuse and recycling), and downstream (deconstruction and disposal) flows. Subsequently, the inventory of flows has localized, regional and global impacts ecological systems such as air, soil, water, and organisms, which are estimated based on a variety of impact categories such as global warming, acidification, ecotoxicity, human toxicity, and many others. Finally, the impacts throughout the phases of the life cycle are interpreted in order to draw conclusions and guide decision making. The International Organization for Standardization (ISO) provides broad guidelines for the procedure by which an LCA is conducted, which are succinctly
described in ISO 14040, the LCA *Principles and Framework*. The four primary stages specified by ISO 14040 are: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation. These stages are often iterative as new knowledge comes to bear and priorities of the assessment change. The relation of these stages to one another and to the resulting applications of an LCA are depicted below in Figure 1.1.

![Life-Cycle Assessment Framework](image)

**Figure 1.1** - LCA framework, including the relationships among the assessment stages and the outcomes.

One of the primary benefits of the LCA methodology is its extreme flexibility, which allows it to be applied to practically any industrial system. Unfortunately, however, this methodological flexibility can make it difficult for systematic application of the method. This inconsistency is shown in the pavement LCA literature in the subsequent section, which motivates the present systematic LCA approach of US concrete pavements.
1.3.2 Prior Literature on LCA of Pavements

From 1996 to 2010, an average of at least one study has been published per year that applies the life cycle assessment methodology to pavements. While this has allowed for an accumulation of knowledge in this field of research, there has not been a clear evolution of the scientific field over this period. In the current pavement LCA literature, there are widely varying and apparently contradictory results. These contradictory results stem from employing different assumptions and applying the LCA methodology in different ways, which is demonstrated below. The lack of a standard and reproducible approach hinders the credibility and resulting utility of the studies.

This study avoids the arbitrary exclusion of primary life cycle phases by making an effort to include all quantifiable life cycle phases. It also avoids the arbitrary selection of pavement case studies on which to perform an LCA by using a standard road classification system developed by a federal agency in order to systematically represent a wide variety of pavement types. The following section surveys the current LCA literature in order to: 1) identify inconsistent selection of life cycle phases and functional units among the studies, and 2) identify a more comprehensive and a more systematic approach for the present research.

Including All Life Cycle Phases

In a recent literature review of pavement LCAs, 12 studies were evaluated for their inclusion of five different primary phases in the pavement life cycle: materials, construction, use, maintenance and rehabilitation, and end-of-life (Santero 2010). Of these 12 studies, not a single study included all five phases, and half of them excluded more than one phase. The present study aims to broadly include all
five life cycle phases, as well as comprehensively include as many of the components of these phases as possible. These include those that have been identified to contribute significant life cycle GHG emissions, as well as have a quantifiable effect with some degree of confidence.

The decision to include or exclude a portion of the life cycle is recommended by the ISO 14000 LCA methodology standards to be deliberated by a “cut-off criteria” (ISO 2006). This is a threshold that is selected based on the contribution to the overall life cycle of the element under consideration. This contribution can either be on a mass basis or environmental impact basis. The definition of a “significant” contribution in the present study is a component that contributes 1% or more of the life cycle GHG emissions. Additional elements are excluded on the basis of being not quantified with certainty or not well understood by the current science.

Choosing Representative Pavements

In LCA parlance, defining the “functional unit” or “unit of service” for a given product is necessary in order to express emissions and impacts in reference to a mathematical quantity. According to ISO 14044, “the scope of an LCA shall clearly specify the functions (performance characteristics) of the system being studied. The functional unit shall be consistent with the goal and scope of the study. One of the primary purposes of a functional unit is to provide a reference to which the input and output data are normalized” (ISO 2006).

The performance characteristics of a pavement can be described in a variety of ways (i.e. by set time, compressive strength, traffic loading, geometric dimensions, etc.), and the functional unit selected is equally variable in the pavement LCA literature. Pavements can provide different levels of
functionality, from supporting low levels of light vehicle traffic to high levels of truck traffic across multiple lanes. The representativeness of a chosen functional unit is a common issue in LCA generally, as it can be difficult and even arbitrary to choose, and can lead to errors from overgeneralizing the results by applying them to non-representative products. Because no two pavements are alike, and no two studies have the same approach, there are inconsistent functional units across the pavement LCA literature, which creates the potential for interpretation error and prevents the comparison of results across different studies.

In the US pavement LCA literature, there are a number of different perspectives on the functional unit of study. Some focus on roads generally (Nisbet et al. 2001; Chan 2007), whereas others specifically focus on highways or interstates (Horvath and Hendrickson 1998; Zapata and Gambatese 2005). In these cases, as with most pavement LCAs, the structures are defined by their ability to carry traffic, since this primarily determines the design of the pavement layer thicknesses. Horvath and Hendrickson (1998), for example, analyzed an interstate highway, and chose 10 million ESALs as representative in order to define the structure. In Chan (2007), 13 different roads in the state of Michigan were selected as case studies for evaluation. In Nisbet et al (2007), the roads are labeled urban collector and highway, but the traffic level and justification for the structure selection are undocumented. There is little attempt in these studies as well as others to take a top-down approach in systematically defining the functional unit, such that it is in reference to a standard for defining pavement classes, and such that they are consistent and thus more easily comparable across studies.

It is not only important to be systematic about the functional unit for the sake of standardization, but this classification approach also allows an understanding of what different components drive the life cycle GHG emissions on different types of roads. For example, the relative
importance of traffic-related issues (such as traffic delay and pavement roughness) is expected to be larger on a high traffic volume road than on a low traffic volume road.

According to the needs identified above in the pavement LCA domain, the first primary goal of the present study is: to quantify cradle-to-grave life cycle greenhouse gas emissions in a systematic and comprehensive way so as to capture a) the primary functional classes of concrete pavements and b) all relevant life cycle phases. This allows for the first time a comparative understanding of how the overall GHG emissions differ according to the character of service of all primary pavement types, as well as how the contributions from the various life cycle components change across these functional types.

To this end, the functional units selected here for analysis come from the US Federal Highway Administration’s definition of pavement functional systems. These include 6 rural functional systems: interstates, other principal arterials, minor arterials, major collectors, minor collectors, and local roads; and 6 urban functional systems: interstates, other freeways and expressways, other principal arterials, minor arterials, collectors, and local roads (Federal Highway Administration 2008). This appeals to a federal administrative body’s definition of pavement types, and has the additional advantage that highway and traffic statistics are collected for each of these functional systems. The traffic data (light vehicles per day, trucks per day, etc.) and geometric data (lanes, lane-widths, etc.) from these statistics allow inference of the pavement designs that constitute each of these systems, which is explained in Chapter 3 of the methodology (Section II). These are used as the functional units for the present LCA in order to accurately and systematically represent the different characters of service that are found in the pavement network.
**Benchmarking National GHG Emissions**

In order to estimate the scale of GHG emissions due to concrete pavements in the US, as well as to set a baseline for future emissions reduction strategies, the present study will quantify the emissions for new concrete pavements that are constructed each year in the US. Using the functional systems from the first part of the analysis, the life cycle emissions for each representative structure can be extrapolated onto the extent of the entire network. Utilizing the functional systems from the first part of the analysis allows this, and also gives perspective on the relative contribution of the different networks for each functional system.

As previously mentioned, there is a GHG inventory that is collected for each economic sector by the Environmental Protection Agency (EPA), including cement plants and vehicle transportation in the US (EPA 2009). But this does not give enough information to obtain a life cycle perspective on the concrete pavement network. In 2009, a study was also by the EPA that took a systems perspective to quantify the GHG emissions associated with providing particular needs which involve many different sectors of the economy, such as provision of food, building air regulation and lighting, etc. (EPA 2009). One of the systems provided is “infrastructure,” which consists of life cycle GHG emissions from constructing and maintaining roads and transporting water. They estimate that 1% of all GHG emissions in 2006 were due to infrastructure. This study is unfortunately insufficient for the present purpose of studying concrete roads alone, because it aggregates all pavement types together (including asphalt, the predominant paving material), which could lead to large errors. Additionally, the study employs an economic input-output approach rather than a process-based LCA, which suffers from aggregation errors, and makes it unclear what physical processes are contributing to the life cycle emissions (Norris 2002). These two reasons not only make the benchmarking effort of concrete pavements alone
inaccurate, but additionally do not offer any guidance as to how to reduce the national life cycle GHG emissions of concrete pavements.

This motivates the present effort to benchmark life cycle GHG emissions of all concrete pavements that are constructed each year in the US. This establishes for the first time a sense of the size of this problem, and a clear benchmark of current emissions as a basis for measuring future annual emissions and reductions over time.

**Identifying GHG Reduction Strategies**

The present study is after one fundamental goal—seeking effective strategies for GHG reduction of concrete pavements. To this end, it evaluates a range of opportunities that have to do with different factors in the pavement life cycle, and then applies them at the national and the project level in order to see the potential reductions that are achievable. This allows for the comparison of different strategies side-by-side, as well as to understand if certain strategies are more appropriate for certain types of roads. No other study has compared such an array of life cycle GHG management strategies side-by-side for concrete pavements.

Some studies have considered some of the present strategies in isolation, or looked at other considerations that are not within the scope of the present strategies. In some studies these opportunities can be inferred from sensitivity analysis. Many studies consider the alternative of moving to different materials, such as asphalt for the pavement wearing course rather than concrete, or cement- or asphalt-treated base materials (Häkkinen and Mäkelä 1996; Treloar et al. 2004). One study that comes close to the present intent is (Mroueh and Tielaitos 2000), which analyzes the impact of
several industrial by-products in order to reduce the cement and aggregate content, including coal ash, crushed concrete waste, and blast furnace slag. A study that was similar in intent but for a different scope was done to see what technologies could be introduced into US cement plants in order to reduce carbon emissions and increase energy efficiency, which had the additional benefit of economic cost-effectiveness for the evaluated strategies (Worrell et al. 2000). None, however, have used this sort of broad brush to see what may be obtainable in terms of GHG reductions at the project and national level for concrete pavements.

The final goal of this thesis is to identify opportunities for GHG reductions of concrete pavements, and to quantify the GHG reduction on a project-level basis and a network-wide basis. This measures for the first time the potential of these strategies for different pavement types, which helps transportation agencies and construction contractors to prioritize reduction strategies for the different types at the project level. This also shows the reduction potential across the entire US concrete pavement network that could be achieved by nationwide policy at the federal level.

1.4 CONCLUSION

This chapter presented the overall motivation for the fundamental goal to reduce life cycle GHGs associated with concrete pavements. This leads to a three-pronged approach that: 1) establishes emissions in a systematic fashion across the various pavement types, 2) benchmarks emissions at the national level, and 3) considers reduction strategies that show the potential at the national level and the project level to reduce life cycle GHGs of pavements. This allows for recommendations to be made to the different agencies that control different functional types of roads, from federally-funded interstates down to local roads built by city departments of public works.
SECTION II: METHODOLOGY

CHAPTER 2: GOAL AND SCOPE OF LIFE CYCLE ASSESSMENT

2.1 INTRODUCTION

This chapter presents the objectives of the LCA, as well as the bounds of the analysis scope. The scope of the LCA presents the system boundary of what pavement processes which have environmental relevance are and are not included in, as well as the cut-off criteria that justify their relevance. Then the impact assessment method as well as data quality requirements are presented.

2.2 GOAL OF LCA

This study establishes a benchmark for the carbon footprint (or global warming potential) of new concrete pavements in the entire US road network, in order to gain insight about how life cycle embodied carbon emissions can be reduced. This requires systematically characterizing the pavement network in a meaningful and accurate way by surmising pavement structures that are representative of the widely variable pavement designs that are found. To that end, the study employs national statistics from the Federal Highway Administration to derive representative structures. Their derivation thereby allows quantification of carbon emissions and prioritization of reduction strategies that can be aimed at 12 functionally different classes of pavements, which are described in Chapter 3. The climate change impact of these structures can then be extrapolated onto the entire network based on the growth of
each functional class network, in order to estimate a national benchmark for newly constructed concrete pavements.

2.3 SCOPE OF LCA

2.3.1 The Product Function and System

The industrial products being analyzed are new concrete pavements, which are designed and constructed primarily to enable safe, expedient automobile traffic. The pavement as a product system is distinct from a roadway, which is a subtle but important distinction (Santero 2009). The decision to build a roadway where one did not previously exist involves a dynamic and complex host of impacts on the broader economy that the new access to mobility entails. While these are important issues, especially given the integral role of road transportation in the economy’s supply chains and the country’s urban design, they are outside of the present scope. Aside from these broader concerns, given that the decision to support a given expected traffic level, the present goal is that the pavement structure can be designed such that the impacts on climate change are reduced.

The spatial extent of the product systems being analyzed is: a length of 1 kilometer of pavement; a width across all lanes, shoulders, and out to the curb for curb-and-gutter designs and out to the edge of the foreslope for other designs; and a depth extending from the subgrade, through the support layers and wearing course, to the surface of the pavement. The functional units of analysis are presented in detail Chapter 3.
2.3.2 System Boundary

A recent literature review looked at 12 life cycle assessment studies on pavements, evaluating their inclusion of five primary phases in the life cycle: materials, construction, use, maintenance/rehabilitation, and end of life (Santero 2010). Not a single one of the studies comprehensively included all five phases. The arbitrary inclusion of certain components within each phase also detracts from the utility of the results.

The following life cycle phases and the components that comprise the system boundary of the pavement system are shown below in Figure 2.1.

Transportation of all paving materials—including cement, aggregate, water, steel reinforcement, fly ash, concrete ready mix—is included in and between phases I, II, and V. Upstream mining, processing and transportation of raw feed for cement production is also included (limestone, gypsum, water, fuels) but is cut-off for upstream fuel and electricity production (such as emissions associated with extracting coal) because of negligible environmental significance (Marceau et al. 2006).

Also not included in the scope of this analysis are the following elements deemed insignificant to the life cycle: capital goods production (excavation and paving machinery, production plant equipment, oil refinery infrastructure, etc.), production of roadway lighting hardware, road paint production and application, and joint sealant.

The data sources and modeling approach are discussed in depth in Chapter 4.
The Federal Highway Administration recommends including not only initial construction costs when considering alternative pavement designs, but also to include rehabilitative activities (FHWA 2003). The temporal scope (or analysis period) of this study begins at new construction—through 40 years of operation, which includes two rehabilitation activities (at years 20 and 30)—and ends at recycling and disposal at the end of life. This corresponds to a design life of 20 years for all pavements.
While concrete pavements often last more than 40 years, the end of life is included in order to evaluate preferred waste management practices. The analysis period and rehabilitation schedules and activities are based on the most common responses in a survey of state agencies’ life cycle cost analysis procedures, which reflect agencies’ experience on how long pavements can predictably last (Rangaraju et al. 2008; MDOT 2009).

2.3.3 Impact Assessment Method

The primary impact considered in the present study is global warming potential (GWP), as measured in carbon dioxide equivalent (CO$_2$e). The two most widely used methodologies for assessing GWP impacts include the Environmental Protection Agency’s TRACI method (Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts), and the Centre for Environmental Studies of the University of Leiden’s “CML” method. Both methods cite the 2007 “Fourth Assessment Report” by the Intergovernmental Panel on Climate Change, but only the CML method has been updated to reflect the latest IPCC data (PE Americas 2011). The present study employs this more up-to-date method based on the 100 year time horizon of greenhouse gas perpetuity. The procedure for characterization and normalization of global warming potential impacts involves deriving the radiative forcing and decay rate of each of the recognized greenhouse gases in terms of their equivalence to carbon dioxide (IPCC 2007). For example, methane has a characterization factor of 25, meaning it has 25-times the effect on global warming potential over the 100 year time horizon. While GWP is a preeminent issue because of concerns about anthropogenic climate change, it is important in future studies to consider other environmental impacts (such as toxic releases, water usage, etc.) in order to inform comprehensive and holistic sustainability efforts.
2.3.4 Data Quality Requirements

In general, the highest quality data that can be obtained is used, in terms of its geographical, technological, and temporal representativeness. Most data are based on national US averages (along with the standard error when available or estimable). Sometimes, midpoint, median, and mode values are used rather than the mean, and will be so indicated. If data is not available on a national scale, state-level data is preferred, then plant or process specific data is preferred, and estimation is used only as a last resort when no data is available, and will be so indicated. The most recent data was always used except for example in the case of domestic cement transportation, which reduced drastically in lieu of importing during the economic downturn of 2008-2010. While average data is always used, statistical variance from the mean value is documented so as to ascertain the significance of the results in the uncertainty analysis phase of the study.

2.4 CONCLUSION

This chapter included: the goals of the LCA, the scope of the LCA and associated cut-off criteria, a description of the impact assessment method, and data quality requirements.

For a discussion of the limitations of this chapter, see Section 7.3.1 below.
CHAPTER 3: CHARACTERIZING THE US PAVEMENT NETWORK

3.1 INTRODUCTION

This chapter presents a detailed description of the systematic procedure to derive the representative concrete pavement structures and their design characteristics for each of the 12 functional systems. A visual representation of the 12 structures is found in Figure 3.3. Then the procedure to extrapolate these representative structures onto the entire US concrete pavement network is presented.

3.2 PURPOSE

In order to benchmark the carbon footprint of new concrete pavements in the United States, ideally there would be continuous reporting of material and energy inputs, as well as emissions and waste outputs that occur throughout the life cycle of every road that is constructed. This is the ideal situation for any given life cycle analysis study, but the data is resource and time-intensive to collect. A model that represents the life cycle with a limited set of inventory data is a way of estimating the inputs and outputs of materials, energy, and emissions. The model created for this study is comprised of information that represents the various life cycle phases for a pavement in general, and it also consists of variables within the model that can be set to represent a specific structure. This can be paired with information on the wide variety of structures that are built each year to quantify the system-wide footprint. But information on the structural designs that constitute the US pavement network is housed
in the disparate silos of contractors and pavement engineers; there is no pavement management system that describes the pavement structures that exist across the US roadway network.

There is, however, a public databank of statistics maintained by the Federal Highway Administration that has useful information on street and highway transportation (Federal Highway Administration 2008). These statistics include year-to-year data on highway infrastructure and vehicle travel that offer an inventory characterization of the entire US pavement network. The added benefit to this repository is that it is categorized by functional system, which groups roads according to the character of service that they provide. The character of service spans a continuum between providing mobility and providing land access—interstates and highways are for rapid, long distance mobility between cities, whereas local roads are more diffuse over a large area and provide access to homes, businesses, and other local destinations. The intermediate functional classes provide a mixture of the two services. Looking at the composition of the pavement network, there are far more lane-kilometers of local roads, as can be seen in Figure 3.1 (Federal Highway Administration 2008). But in terms of the amount of traffic on each road, there is much more traffic density on the roads that provide mobility. In Figure 3.2, the traffic distribution is shown for 9 of the 12

![Figure 3.1 - Lane-kilometers of the US pavement network by functional system.](Image)
FHWA functional systems (Federal Highway Administration 2008). Distributions are not available for the other three systems, but the mean average annual daily traffic (AADT) for these is as follows: 574 vehicles/day on rural “minor collectors,” 177 vehicles/day on rural “local roads,” and 980 vehicles/day on urban “local roads,” see Appendix 1 for calculation (Federal Highway Administration 2008).

The different “characters of service” for each FHWA functional system correspond to the different functional units or units of service that are analyzed in the present LCA. The mean values in Figure 3.2 (marked in red) are the traffic levels that are taken as representative of each structure. The additional benefit is that the recommendations that result from this analysis can be directed at the different agencies that have control over each class of road.
3.3 REPRESENTATIVE PAVEMENT STRUCTURES

Deriving representative structures for the various FHWA functional systems cannot be straightforward given the widely varying character of service that pavements can provide, as well as different engineering practices that can meet those service needs. Pavement design in the United States has largely been a function of the experience of pavement engineers that operate within a given jurisdiction, as well as the regulatory bodies that mandate policies in that jurisdiction at the various local, state, and federal level in Departments of Transportation (DOTs). The pavement engineering practices are influenced by climate, budgetary, historical, and other factors, and can vary significantly from place to place. However, standardization of practice is important for consistency within a region as well as interoperability across regions.

To this end, the transportation departments in all 50 US states convene on the American Association of State Highway and Transportation Officials, which was founded in 1914 in order to integrate across the various transportation policies. This includes the derivation of pavement design policies, guidelines, and equations that have benefited over time from a diverse array of empirical observations and subsequent adjustments. As a result of this convergence, the AASHTO empirical equations are commonly provided by state DOTs and used by pavement engineers. These equations relate observed or measurable phenomena (pavement characteristics) with outcomes (pavement performance). The 1993 AASHTO Guide for Design of Pavement Structures is employed in the present study to derive pavement structures that are representative of the US pavement network for each FHWA functional system. Among the various AASHTO guides existing in 1999, 65% of the 35 states indicated in a survey that they use the AASHTO 93 design procedure (Newcomb and Birgisson 1999). AASHTO released the Mechanistic-Empirical Pavement Design Guide in 2004, which transitioned from
purely empirically based design procedures, to a mechanistic-empirical approach which allows for analytical modeling capabilities. This was also considered for the present study, but evidence shows that this is less commonly employed within state DOTs because of its relative novelty (Massachusetts Highway Department 2006).

3.3.1 The AASHTO 93 Design Procedure for Concrete Pavements

The basic empirical equation in the AASHTO 1993 Guide for designing rigid (i.e. concrete) pavements is:

Equation 3.1 - AASHTO 93 design equation for rigid pavements.

\[
\log_{10}(W_{18}) = Z_R \times S_o + 7.35 \times 10^2 \left( D + 1 \right) - 0.56 - \frac{10^2}{1 - \left( \frac{\Delta PSI}{1.5} \right)} + \left( 4.22 - 0.32 \rho_t \right) \times 10^2 \times 10^2 \left( \frac{\Delta PSI}{1.5} \right) + \left( \frac{18.4}{\rho_t} \right) \times 10^2
\]

where:  
- \( W_{18} \) = predicted number of 80 kN (18,000 lb.) ESALs  
- \( Z_R \) = standard normal deviate  
- \( S_o \) = combined standard error of the traffic prediction and performance  
- \( D \) = slab depth (inches)  
- \( \rho_t \) = terminal serviceability index  
- \( \Delta PSI \) = difference between the initial design serviceability index, \( p_0 \), and the design terminal serviceability index, \( p_t \)  
- \( S' \) = modulus of rupture of PCC (flexural strength)  
- \( C_d \) = drainage coefficient  
- \( J \) = load transfer coefficient (value depends upon the load transfer efficiency)  
- \( E_c \) = Elastic modulus of PCC  
- \( k \) = modulus of subgrade reaction
The above inputs to this equation are explained in depth below as they apply to deriving representative concrete structures.

### 3.3.2 Predicted Traffic Loading Input

$W_{18}$ is the predicted traffic loading that is expected over the design lifetime of the pavement, as measured in the number of 80 kN-equivalent single axle loads (ESALs). This invokes the two variables to which the pavement designs are most sensitive: traffic volume and pavement service life.

These traffic loadings are derived from FHWA Highway Statistics tables VM-202 “Annual vehicle-miles of travel, by functional system, national summary” and HM-20 “Public road length - 2008 miles by functional system,” and dividing the national annual vehicle-miles of travel (VMT) on each functional system by the extent of that system to result in the average vehicles per year per functional system (Federal Highway Administration 2008). Because passenger vehicles and trucks have different ESALs on a per vehicle basis, the portion of the previous result constituted by truck traffic was disaggregated by using the VMT per vehicle type from table VM-1 “Vehicle miles of travel and related data, by highway category and vehicle type.” AADT and AADTT for the 12 functional systems are shown in Appendix 1.

In order to quantify the variability of annual traffic across different roads of each functional system, as well as the sensitivity of the resulting designs to the variable traffic levels, pavement designs were also derived to represent a high-end and a low-end traffic loading for each functional system. The FHWA *Highway Statistics* gives traffic distribution data for each functional system, but the data is grouped differently for each system, and grouped in unequal intervals, in table HM-57 “Functional system length – 2008 miles by average daily traffic volume” (Federal Highway Administration 2008). In
order to obtain high- and low-end values systematically, quantiles were estimated for the grouped data using linear interpolation, which assumes no parametric form for the distribution of the data. For example, the length of rural interstates is 48,651 km (30,230 mi), and 11,071 km (6,879 mi) have an AADT of less than 10,000—and linear interpolation estimates the first sextile (six quantiles of 8,108 km each) to have a corresponding AADT of 7,324. The first and fifth sextiles were used as high- and low-end traffic loadings, because between this interval captures 4/6 or 67% of all traffic on a functional system, which is approximately equal to the proportion of values that are within one standard deviation away from the mean for a normal probability distribution (68.3%). All high- and low-end traffic loadings and their corresponding design calculations are shown in Appendix 1.

A 20-year design is taken to represent that average design life, as this is the most common year that state DOTs conduct the first rehabilitation of concrete pavements, according to a survey on life cycle cost analysis (LCCA) practices within state DOTs (Rangaraju et al. 2008; MDOT 2009). Traffic loadings on an annual basis for 2008 are multiplied by the design lifetime to obtain the value for pavement lifetime ESALs. The traffic growth rate on these networks was ignored, as this value was consistently between -1% and +1% per year for the 10 year interval between 1999 and 2008, and therefore has a negligible impact on the pavement designs.

3.3.3 Reliability and Serviceability Inputs

The reliability of the pavement design is the probability that a pavement section will perform satisfactorily over the traffic and environmental conditions for the design period (AASHTO 1993). Table 3.1 gives AASHTO’S recommended levels of reliability, which determine $Z_r$ and $S_o$. 

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### Table 3.1 - Suggested levels of reliability for various functional classifications (from AASHTO 1993)

<table>
<thead>
<tr>
<th>Functional Classification</th>
<th>Recommended Level of Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Urban</td>
</tr>
<tr>
<td>Interstate and Other Freeways</td>
<td>85 - 99.9</td>
</tr>
<tr>
<td>Principal Arterials</td>
<td>80 - 99</td>
</tr>
<tr>
<td>Collectors</td>
<td>80 - 95</td>
</tr>
<tr>
<td>Local</td>
<td>50 - 80</td>
</tr>
</tbody>
</table>

The serviceability life is the difference in present serviceability index ($\Delta$PSI) between the present construction and the end-of-life of the pavement. Post-construction PSI generally ranges from 4.0-5.0, while the terminal serviceability ($p_t$) ranges from about 1.5-3.0 depending on the type of road (interstate, arterial, etc.).

Assumed inputs for reliability and serviceability are included in pavement design calculations in Appendix 1.

### 3.3.4 Material Property Inputs

The remaining inputs to the AASHTO design procedure are parameters that pertain to the material properties of the subgrade, base layers, and concrete slab design. These include the PCC slab depth ($D$), flexural strength ($S'_c$), drainage coefficient ($C_d$), load transfer coefficient ($J$), elastic modulus of PCC structure ($E_c$), and modulus of the subgrade reaction ($k$).

Dowel bars are used on all interstates, expressways and other freeways, to help support load transfer of the vehicle for traffic volumes above 3 million ESALs. The assumed load transfer coefficient is $J = 3.2$ where the concrete slabs are unreinforced, and $J = 2.8$ on all interstates, freeways, and principal
arterials, as well as urban minor arterials. These structures have steel reinforcing dowels to support the load transfer between slabs, per section 2.4.2 of the design guide (AASHTO 1993).

The moduli of the subgrade reaction for this design procedure were determined from historical data provided in (ACPA 2000). A conventional 6” granular base material is assumed for the base structure of all designs with traffic volume greater than 1 million ESALs. Below this traffic volume, a type of pavement degradation known as slab pumping is not a predominate concern, and so no base layer is put in place (AASHTO 1993). The present design procedure employs a k-value of 150 for designs with a 6” granular base and k = 100 for designs with no base (ACPA 2000).

Standard concrete mix designs vary by the state agencies that specify them. In the ACPA’s online “Agency Practices Explorer,” they list the mix designs by agency, which vary in cement content from 440-611 lb/yd$^3$ (ACPA 2011). The most common value for cement content used by 13 of the 27 agencies is a 565 lb/yd$^3$ mix, which is employed for the present designs. Also, 11 of the 30 agencies that specify flexural strength of 650 psi at 28 days of set time, which is employed as the $S_c$ value here.

This design procedure uses drainage coefficient ($C_d$) of 1, which corresponds to the AASHTO road test conditions (AASHTO 1993). The elastic modulus of the PCC structure ($E_c$) is 4,200,000 psi, which is also the standard value from the AASHTO road test.

Once the above parameters are input to the AASHTO 93 design equation, the PCC slab depth is the primary parameter of interest that determines how thick the concrete structure must be to reliably support the given traffic loading for the entire pavement service life. The depths that result from the present design procedure are below, rounded to the nearest half inch. All input parameters are listed in the pavement design calculations in Appendix 1.
3.3.5 Number of Lanes and Lane Width

In order to obtain the number of lanes for each representative structure design, operations were performed on FHWA Table HM-60 “Functional System Lane-Length 2008 Lane-Miles” and Table HM-20 “Public Road Length - 2008 Miles by Functional System” (Federal Highway Administration 2008). Dividing the total number of lane-miles by the total number of miles for each functional system gives an average number of lanes, which is an indication of the composition of the entire network. For example, the average number of lanes on the urban “other principal arterials” in 2008 was 3.5, which indicates an approximate composition of 75% of the network length having 4 lanes and 25% having 2 lanes. The mode values were chosen for each case since it is the most commonly occurring, and because it is difficult to make sense of use partial lane numbers that would obtain if an average were used.

The representative lane widths were obtained from Table HM-53 “Functional System Length - 2008 Miles by Lane Width” (Federal Highway Administration 2008). Lane widths frequencies are tabulated by discrete widths, classified as <9, 9, 10, 11, 12, and >12 ft widths. From Table HM-53, the median values were derived through linear interpolation as described in the section above on predicted traffic loading. Linear interpolation also allowed for the first sextile and fifth sextile lane widths to be calculated, in order to accurately represent variability. Data is not available for three of the classes, so rural “major collectors” lane widths were used as representative of rural “minor collectors” and rural “local roads.” For urban “local roads,” 9 ft lanes with 7 ft parking lanes are used per AASHTO guidelines (AASHTO 2005).
3.3.6 Shoulder and Foreslope Design

Designs for the traffic lanes of the structures representative of the FHWA functional classes were derived above using the AASHTO design procedure, in conjunction with FHWA public road statistics and data on common state transportation agency practices. The general design procedure applies identically to high- and low-traffic roads, as well as to urban and rural settings. There are other elements at the periphery of these traffic lanes, however, that are designed according to the surrounding urban and natural environments, and user utility and safety. These include roadway lighting, inner and outer shoulders, and pavement foreslope. The present analysis does not include roadside curbs or ditch and backslope elements, as these are considered outside the purview of the pavement’s function to enable vehicle transportation. AASHTO’s *A Policy on Geometric Design of Highways and Streets* provides standardized guidelines for shoulder and foreslope designs, which are employed to complete the present structures. All shoulder and foreslope designs are shown in the next section.

Shoulders are a portion of the pavement adjacent to the traffic lanes which allow for vehicle stops, emergency use, and lateral structural support of the wearing course, base, and subbase layers. The desired width of the inner and outer shoulders depends primarily on the number of traffic lanes and the traffic volume (AASHTO 2004). The assumed shoulder design is a very significant assumption in terms of sensitivity of the LCA results, due to the large volume of concrete that is in the shoulders, as well as the wide variety of possible shoulder designs that are actually constructed.

The foreslope refers to aggregate base material that is used to gradually taper the road from the height of the shoulder at the margin down to the subgrade. This must be sufficiently flat so that an out-of-control vehicle does not flip over when exiting the roadway, or can potentially regain control.
(AASHTO 2004). A minimum slope of 4H:1V, or four units of horizontal length for every one unit of vertical drop, is used for all structures per minimum AASHTO design requirements.

3.3.7 Representative Structures for 12 Functional Systems

Details on the representative geometry and material composition that result from this design procedure are presented below in Figure 3.3 for all 12 FHWA classes. The structural depth of each layer is to scale, as well as the width of each design element across the roadway, but the depth and width are scaled independent of one another—hence the foreslope designs appear much steeper than they actually are. Where “one direction” is indicated, there is another equivalent structure carrying traffic in the opposite direction, and there is a central median which is not included in the analysis. Otherwise, all roads serve bidirectional traffic.
Figure 3.3 - Representative Structures for 12 Functional Systems

**Rural Interstate (one direction)**

- foreslope | 4 ft sh. |
- 11.5” JPCP (with 1.5” dowels)
- 6” Granular Base
- Prepared Subgrade
- (2) 12 ft lanes | 10 ft shoulder |

**Rural Other Principal Arterial**

- foreslope | 8 ft shoulder |
- 8” JPCP (with 1.25” dowels)
- 6” Granular Base
- Prepared Subgrade
- (2) 12 ft lanes | 8 ft shoulder |


Rural Minor Arterial

foreslope | 8 ft shoulder | (2) 12 ft lanes | 8 ft shoulder | foreslope

7.5" JPCP

6" Granular Base

Prepared Subgrade

Rural Major Collector

foreslope | 6 ft sh. | (2) 11 ft lanes | 6 ft sh. | foreslope

6" JPCP

6" Granular Base

Prepared Subgrade
Rural Minor Collector

foreslope | 5 ft sh. | (2) 11 ft lanes | 5 ft sh. | foreslope

5" JPCP

Prepared Subgrade

Rural Local Road

2 ft sh.

foreslope |  | (2) 11 ft lanes |  | foreslope

4" JPCP

Prepared Subgrade
Urban Interstate (one direction)

foreslope  |  10 ft shoulder  |  (3) 12 ft lanes  |  10 ft shoulder  |  foreslope

6" Granular Base

12" JPCP (with 1.5" dowels)

Prepared Subgrade

Urban Other Freeway (one direction)

foreslope  |  4 ft sh.  |  (2) 12 ft lanes  |  10 ft shoulder  |  foreslope

6" Granular Base

11" JPCP (with 1.5" dowels)

Prepared Subgrade
**Urban Other Principal Arterial**

- Curb | 8 ft shoulder | (4) 12 ft lanes | 8 ft shoulder | curb
- 8.5" JPCP (with 1.25" dowels)
- 6" Granular Base
- Prepared Subgrade

**Urban Minor Arterial**

- Curb | 8 ft shoulder | (2) 12 ft lanes | 8 ft shoulder | curb
- 7" JPCP (with 1.25" dowels)
- 6" Granular Base
- Prepared Subgrade
Urban Collector

- curb | 8 ft parking | (2) 11 ft traffic lanes | 8 ft parking | curb
- Prepared Subgrade
- 6.5” JPCP

Urban Local Road

- curb | 7 ft parking | (2) 9 ft traffic lanes | 7 ft parking | curb
- Prepared Subgrade
- 5” JPCP
3.4 EXTRAPOLATING TO THE ENTIRE NETWORK

The above structures were so designed because the number of lanes, lane widths, shoulder widths, etc. were the most common and therefore are discrete, project-level designs that represent each functional system. The results for these structures are extrapolated onto the entire pavement network in order to estimate the national carbon footprint for new concrete construction in each class. Where additional information is available, a better estimate from extrapolation can be obtained by using average and median values rather than mode values. A particularly important assumption is the number of traffic lanes, which are selected as discrete values in the above procedure, but are altered for extrapolation to the network. The mean number of lanes for each functional system is obtained by dividing the total number of lane-miles (from Table HM-60) by the total number of miles (Table HM-20). These values are in Appendix 1.

Since a mean value was unavailable, the median lane width was derived from Table HM-53 using linear interpolation where possible. Such data is unavailable for rural “minor collectors,” rural “local roads,” and urban “local roads,” so the discrete values from the design procedure were taken as representative for the extrapolation.

No other structural elements were changed, including: design thicknesses, inclusion of dowels, shoulder and foreslope designs. FHWA does not collect data on these design aspects that might otherwise inform the extrapolation.

Once the impact for each functional unit is quantified in this manner, combining it with the growth rate of the concrete pavement network in each functional system gives a projection for the GHG emissions occurring every year in the US from new concrete pavement construction. Year-on-year
growth rates of each functional system network were obtained using 10 years of historical data for the period of 1999-2008, using table HM-220 “Public Road and Street Length: Mileage by Functional System” (Federal Highway Administration 2008). According to this table, it appears that the entire rural network is decreasing in extent, while the urban network steadily increases. This is actually an artifact of reclassification of roads from rural to urban based on population growth in rural areas. In order to estimate growth of the separate rural and urban networks before reclassification, the growth rate of the combined systems was used instead. For example, rural local roads decreased from 3,375,235 km in 1999 to 3,276,974 km in 2008 (-3% growth), while urban local roads increased from 1,361,642 km to 1,714,846 km for the same period (26% growth). The combined growth for all local roads from 4,736,869 km in 1999 to 4,991,820 km in 2008 (5% growth) was used for both rural and urban local road network growth rates, thereby ignoring reclassification for the extrapolation analysis.

3.5 CONCLUSION

This chapter presented a procedure for representing the design characteristics for 12 FHWA functional classes of US concrete pavements, and then a procedure to extrapolate those representative structures onto the entire US concrete pavement network. For a discussion on the limitations of the procedure for representing the 12 pavement classes, see Section 7.3.2. For validation of the extrapolation procedure and results, see Section 7.2.2, and for discussion of the sensitivity to the pavement network growth rate, see Section 7.2.4.
CHAPTER 4: LIFE CYCLE ASSESSMENT MODEL

4.1 INTRODUCTION

In this chapter, the environmental impact modeling of concrete pavements approach is presented. First is a discussion of the life cycle modeling software, GaBi 4 (PE 2011). Second, the data sources, calculations, and assumptions that go into the model are presented in order to accurately represent all materials and processes that are within the system boundary over the 40 year analysis period. This is done for five primary life cycle phases: materials extraction and production, pavement construction, pavement rehabilitation, pavement use, and end-of-life recycling and disposal.

4.2 DESCRIPTION OF THE PAVEMENT LCA MODEL

For modeling the life cycle of concrete pavements, the LCA software GaBi 4 by PE International is used as the analysis platform. GaBi 4 allows for building life cycle models, generating life cycle inventories for the model, comparing different scenarios, and conducting basic statistical analysis. The platform allow for data to be extracted from the existing database, which is procured by PE International, as well as incorporating outside data to create industrial processes from scratch.

One of the primary benefits of GaBi 4 for the present purpose is that the modeling of industrial processes and environmental flows into and out of these processes can be parameterized, meaning symbolic variables that represent physical quantities or properties are incorporated into the model. These parameters can then be operated on to allow for complex calculations, and can be defined in terms of probability distributions and scenarios. For example, the cement content as a percent of the...
concrete mix is defined as parameter “C.perc” in the GaBi 4 model, and a mean, standard deviation, and maximum range can be specified for the variable as well. This enables understanding how the resulting life cycle impacts change under a variety of different scenarios, such as the different pavement designs presented in the previous chapter.

Additionally, parameterization within GaBi 4 allows for estimation of variability and includes a sensitivity analysis tool that enables understanding the sensitivity of the results to variation of the input parameters. One limitation of this tool is that it assumes all parameters with a specific standard deviation have a uniform distribution, although the precise parametric form of the distribution may not be known. In this case, a triangular distribution would be more representative. In other cases, the distribution might be better estimated with Poisson distribution, or other distribution types. Despite this limitation, the normal standard deviation for many of the data are included in the GaBi model for sensitivity analysis, and are so indicated below whenever possible. Their influence on the model results are presented in Chapter 5.

Below is a partial screenshot from GaBi, showing processes within the concrete pavement model in the background (at left), and one process open in the foreground (at right). This is intended to demonstrate the basic modeling functions within GaBi. It firstly shows how some of the processes link up, such as gasoline and diesel combustion, which are inputs into the process representing “fuel consumed due to roughness.” It also shows the “Albedo” process open on the right side, which shows the symbolic parameters used in this process, such as “CO2e,” which is calculated based on other parameters, and also corresponds to an “Output” of the process for the environmental flow “Carbon dioxide emissions to air.”
Figure 4.1 - Screenshot of GaBi model, including processes on left and open process on right with parameters.

In the following Sections (4.3-4.7), the data sources, assumptions, and calculations that are incorporated into the model are presented. Figure 2.1 (Chapter 2 above) contains a visual diagram of all the life cycle phases and components that are included below.

4.3 MATERIALS EXTRACTION AND PRODUCTION

Table 4.1 summarizes all the key factors for the materials and processes in the pavement life cycle. Data derived by PE International and compliant with the ISO 14040 LCA standards are used for all electricity and fuel inputs (including gasoline and diesel), which are cradle-to-grave LCAs and representative of US national averages (PE 2011).
4.3.1 Cement

For cement, the life cycle inventory (LCI) data is drawn from a prior study based on a US national survey of cement production, which include the following in the life cycle inventory for cradle-to-gate production (Marceau et al. 2006):

- Quarry and crush: extracting raw material from the earth, crushing to 5-cm (2-in.) pieces, and conveying and stockpiling.
- Raw meal preparation: recovering materials from stockpiles, proportioning to the correct chemical composition, and grinding and blending.
- Pyroprocess: processing raw meal to remove water, calcining limestone and causing the mix components to react to form clinker, cooling and storing the clinker.
- Finish grind: reclaiming the clinker from storage, adding gypsum and grinding to a fine powder, conveying to storage, and shipping in bulk or in bags.

Per Marceau et al. (2006), the average life cycle greenhouse gas emissions per kg of cement production is 1.067 kg CO₂e. The cement LCA was done according to ISO 14040 and 14041 standards for life cycle assessment. The emissions for different cement production technologies (wet, long dry, preheater, and precalciner) are shown, which result in a calculated standard deviation of 9.8%.
Figure 4.2 - Steps in the cement manufacturing process: (1) quarry and crush, (2) raw meal preparation, (3) pyroprocess, and (4) finish grind [from Marceau et al. 2006].

4.3.2 Fly Ash

Fly ash is a supplementary cementitious material (SCM) that can substitute limestone in the raw feed for cement production, or alternatively can substitute for cement in the concrete mixture. Both present a large opportunity to reduce life cycle GHG emissions of concrete, and actually lend beneficial physical properties to the concrete such as increased strength. About 1.1 Mt were used in the United States in all cement kilns in 1996, which is less than 1% of the raw meal volume for that year (135 Mt) (Low 2005). The average fly ash substitution rate in the raw feed for facilities surveyed in the Marceau, et al study in 2006 is also less than 1%, which means very few of these facilities produce significant quantities of blended cements. Fly ash presents a significant opportunity for reducing life cycle GHG of concrete, which will be evaluated in Chapter 6. The data for the life cycle emissions for fly ash
production was drawn from the PE database within *GaBi 4*, and has an associated emission factor of 0.01 kg CO$_2$e per kg fly ash due to upstream transport.

### 4.3.3 Aggregate

Aggregate for concrete production is a mixture of fine and coarse aggregate that, depending on their quality and grading, have a profound influence on the properties and performance of the concrete mixture. The total amount of aggregates within a mix is usually a fixed percentage of the volume, however, the ratio between coarse and fine aggregates change based on the design criteria for each pavement type; coarse aggregates vary from 45 to 65 percent and fine aggregates range between 20 to 35 percent of the total mass (AASHTO 1993; Mallick and El-Korchi 2009). Aggregate is also used in the base and foreslope material, and can also be of varying grades and materials. This often consists of crushed recycled concrete that is used as a base material—which is discussed in Section 4.7 below.

Concrete aggregate consists of coarse and fine aggregates and approximately account for 80% of the concrete mixture (Mallick and El-Korchi 2009). The required energy cited in different sources for production of a ton of aggregates varies from 21 to 74 MJ per ton with a nominal value of 53 MJ diesel energy per ton of aggregate and accounts for 100% of the energy consumed in raw materials extraction and initial transformation (Zapata and Gambatese 2005). This value is used to obtain an emission factor of $3.2 \times 10^{-3}$ kg CO$_2$e per kg of material, with an estimated standard deviation of 32% based on the variable range cited in different literature sources.

### 4.3.4 Steel

Since concrete is incapable of carrying the traffic-applied tensile stresses, steel is the reinforcing element in concrete pavement that carries these forces. Emissions for production of reinforcing bar
(rebar) were obtained by the 2010 World Steel Association global LCI for reinforcing bar, which includes accounts for closed loop rebar recycling. No statistical variability is available.

<table>
<thead>
<tr>
<th>Material</th>
<th>GHG Emissions Factor (kg CO\textsubscript{2}e / kg material)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate</td>
<td>0.0032 ($\sigma = 1 \times 10^{-3}$)</td>
</tr>
<tr>
<td>Concrete mixing</td>
<td>0.0004</td>
</tr>
<tr>
<td>Cement</td>
<td>1.067 ($\sigma = 0.105$)</td>
</tr>
<tr>
<td>Steel dowel bar</td>
<td>0.00055 x $10^{-4}$</td>
</tr>
<tr>
<td>Placement</td>
<td>0.0025</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 4.1 - Inventory data for major pavement materials and processes

4.4 PAVEMENT CONSTRUCTION

4.4.1 Concrete Mixing

The emissions from concrete mixing at a ready mix plant are $4.0 \times 10^{-4}$ kg CO\textsubscript{2}e per kg of material, assuming diesel fuel is used in the concrete mix machinery (Zapata and Gambatese 2005).

4.4.2 Onsite Equipment

Consumption of energy during placement of both types of pavement depends on the amount of diesel fuel used by the onsite equipment necessary for the operation. Typical equipment for pavement placement for concrete pavements includes: a paver, tiner/cure machine, pickup trucks, and a small loader (Zapata and Gambatese 2005). The emissions concrete pavement placement is $2.5 \times 10^{-3}$ kg
CO$_2$e per kg of concrete pavement. During the construction phase, traffic delay due to lane closures and detours may occur during the construction phase, which are described below in Section 4.6.6.

### 4.4.3 Transportation

Four transport legs are accounted for: i) fuels and materials from quarry to cement plant, ii) cement, water and aggregate materials from source to ready mix plant, iii) base material, steel reinforcement and ready mix from source to paving site, and iv) transport of reclaimed steel, concrete, and base material at end of life.

The average distance, standard variance, and number of tons shipped by each transport mode (truck, rail, and barge) are given in the commodity flow survey of 2007 for cement, aggregate, and steel (BTS 2007). Transportation distances by mode for these materials are shown in Table 4.2. For cement, the same is given domestically for truck and barge transport only. Net imported cement constituted 20.4% of apparent consumption between 2005-2008, the largest amount of which comes by barge from China, constituting 22% of imports (USGS 2010). Guangzhou, China to San Francisco, CA is used to model the distance imported cement travels (11,000 km). Less than one percent of construction aggregates are imported, with 94% of imports coming from Canada and Mexico. The distance from CAL-Bechelt operation in British Columbia, the largest gravel mine in North America in 2002, to San Francisco (1600 km), serves as a proxy for barge transport of imported aggregates (Robinson 2002). The distance reclaimed cement travels at the end of life is approximated by the distance base aggregate material travels from source to the pavement site, since many aggregate suppliers also recycle concrete.
The following PE transport data are used: class 7 medium heavy-duty diesel trucks for the US for all truck transport except ready-mix transport which is a 50,000 lb payload tank truck; rail cargo trains for all train transport; and river freight ships for all barge transport.

<table>
<thead>
<tr>
<th>Material</th>
<th>Truck Distance (st. dev) [% by mode]</th>
<th>Rail Distance (% by mode)</th>
<th>Barge Distance (% by mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate¹</td>
<td>50.3 km (12.4 km) [61%]</td>
<td>507 km (25.1 km) [27%]</td>
<td>169.9 km (46.5) [12%]</td>
</tr>
<tr>
<td>Cement</td>
<td>167.4 km² (60 km) [70%]</td>
<td>-</td>
<td>5150 km (2575 km) [30%]</td>
</tr>
<tr>
<td>Demolished concrete</td>
<td>50.3 (12.4 km) [100%]</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.2 - TRANSPORT Distances by mode for various materials

4.5 PAVEMENT REHABILITATION

Major maintenance and rehabilitation is performed over the analysis period in order to keep the pavement in reliable condition to support traffic. Routine periodic maintenance is not included on the base on the assumption that these activities are typically small (less than 1%) relative to the other life-cycle GHG emissions. Although this assumption is echoed in the literature (e.g., Athena 2006), future work is needed to verify its appropriateness. The rehabilitative activities that occur during the 40 year analysis period are based on the most common responses in the state agency LCCA survey (Rangaraju et al. 2008; MDOT 2009). New construction is assumed to last 20 years before being rehabilitated (11 of 27 survey responses), then the second rehabilitation occurs at year 30 (10 of 24 responses).

The rehabilitation activity is also described in the survey, and most agencies specify fully replacing a certain percentage of the slabs, and diamond grinding the entire surface. Four percent patching is the most common value specified in the survey, which also falls under the moderate slab

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¹ Calculated combining USGS data for “Natural Sands” (SCTG 11) and “Gravel and Crushed Stone” (SCTG 12) in proportions according to 31% sand and 48.8% gravel according to material flow analysis (Low 2005; USGS 2010).
² (Miller and Osborne 2010)
replacement range (2-5%) within *RealCost* (CALTRANS 2007). The range in the survey is 0.5%-5% for the first rehabilitation, which is used as the standard deviation, but this ranges up to 30% in the survey for the second rehabilitation. According to the International Grooving & Grinding Association, the diamond grinding equipment requires an average of 1576 L gallons of diesel fuel per lane-km (IGGA, 2009). This is equivalent to 5.6 metric tons CO₂e per lane-km. Inventory data for the materials, construction, and transportation used in M&R is consistent with the approach described in Sections 4.3 and 4.4 above.

During rehabilitative activities, lanes must be closed and traffic may be delayed, which can have a significant life cycle impact if vehicles queue or are detoured. The impacts from traffic delay are discussed below in Section 4.6.6.

### 4.6 USE PHASE

Table 4.6 summarizes all key input parameters for the use phase components of the life cycle.

#### 4.6.1 Albedo

Albedo is a measure of how strongly the pavement surface is able to reflect sunlight. This has a two-fold effect on the greenhouse gas emissions during the use phase: through radiative forcing, and through the urban heat island effect. Radiative forcing refers to the surface’s ability to reflect incoming light back out of the earth’s atmosphere, which tends to cool the earth’s climate system. Urban heat island refers to the pavement’s effect on the ambient air temperature, which indirectly affects GHG emissions by changing the heating and cooling needs of proximal buildings.

The climate impact of radiative forcing depends only on the parameter of pavement color, and is measured on a scale of 0 (pure black) to 1 (pure white) (Goode 2001). This value normally ranges from
0.25 to 0.40 for concrete pavements, which varies according to aggregate albedo and the age of the concrete, since it tends to darken slightly as it ages. The midpoint of 0.325 is taken as the average albedo during the analysis period, and the zero baseline for attributing the effect to the life cycle impact (Akbari 1999). The Akbari 1999 study estimates that an equivalent of 2.55 kg CO2e is emitted per 0.01 decrease in albedo per square meter of pavement. It should be noted that this is not an effect of greenhouse gases, so the impact is estimated based on its equivalence to greenhouse gas emissions for the 40 years that the pavement is in place. To attempt to reduce the life cycle climate impact of pavements by whitening them is a geoengineering approach rather than a preventative approach. Geoengineering is often viewed as a “Plan B” approach, because of complex uncertainties such as regional impacts, and potential difficulties of international policy harmonization since one country’s geoengineering affects the whole planet (Shepherd 2009). For these and other reasons, prevention by reducing emissions is generally preferred.

The global warming potential of the radiative forcing effect is estimated to be about 10 times larger than that of urban heat island, even in a hot climate with a dense population. While the radiative forcing effect is independent of the pavement site, the urban heat island effect depends on features of the local urban population center that contribute to the effect of the heat island on cooling and heating needs. This includes population density and the average annual temperature of the local climate. The normal range maximum is given by a study done to measure the urban heat island effect in the warm climate of Los Angeles, which is then divided out by the total area of paved surfaces to obtain the increase in air conditioning electricity demand, creating an increase in carbon emissions of 4.85 g CO2e per 0.01 decrease in pavement albedo per square meter (Rosenfeld et al. 1998). It should be noted that the average annual climatic conditions are not the same as in urban Los Angeles, so this effect is
probably overestimated. But the impact of this lack of representativeness on the overall results is small because the combined albedo effect is dominated by radiative forcing.

As a potential GHG reduction opportunity, the benefit of whitened concrete pavements is explored in Chapter 6 of this thesis. Whitening pavements also influences pavement lighting demands. The calculations and assumptions for the reduction scenario can be found in Chapter 6.

4.6.2 Carbonation

Much of the carbon dioxide that was originally liberated from limestone in the cement production process rebinds to Ca(OH)$_2$ in the cement by what is known as carbonation. This effect depends mostly on the compressive strength (and thus air penetration) of the concrete, as well as the average annual temperature in the ambient climate. Carbonation ranges from a low of 1.4% re-absorption for high-strength concrete buried under a sealing layer, to a high of 15% re-absorption for exposed low-strength concrete in a warm North American climate (Santero and Horvath 2009). The 15% re-absorption threshold is assumed while the pavements are in place, most of which happens in the first few years because the depth of carbonation is proportional to the square root of time that has passed, assuming a carbonation depth of 8.5 mm. The surface concrete that becomes carbonated is completely removed with diamond grinding with each rehabilitation activity, and uncarbonated concrete is then exposed to the air and able to absorb carbon dioxide from the environment at the original rate of carbonation, an effect which is included in the model. Once the concrete is broken up and stored at a landfill, much more surface area becomes exposed to the atmosphere, and so the theoretically-achievable limit of 75% re-absorption is assumed (Nielsen and Glavind 2007).
4.6.3 Fuel Consumption from Pavement Vehicle Interaction

Fuel consumption is a major contributor to GHG emissions within the transportation sector, accounting for about 23% of total US GHG emissions (EPA 2009). Vehicle fuel efficiency is affected by properties of the pavement, and two primary effects have been identified in the literature as influencing vehicle fuel consumption: pavement roughness and pavement structure (Santero and Horvath 2009). A small change in vehicle fuel consumption due to pavement vehicle interaction has a potentially large effect on the overall impact of pavements depending on traffic volume on that roadway. In order to understand the relationship between fuel consumption of vehicles and pavement, various factors that impact the energy and fuel consumption of vehicles are presented here.

From the standpoint of a vehicle’s overall fuel use, there are two primary categories for fuel loss: the fuel used before and the fuel used after the vehicle driveline. The first category includes engine loss, accessories, and standby power, which consume the majority of a vehicle’s fuel. The fuel used after the driveline is from overcoming forces resisting the vehicle’s forward propulsion—primarily air drag and rolling resistance. These interact with aspects of the pavement materials, such as the stiffness of the structure, the smoothness of the pavement surface, the pavement temperature and thermal radiation. Naturally, a vehicle consumes less fuel on a smooth, stiff pavement with low density (and high temperature) air for the vehicle to counteract than it does on a rough, less stiff structure with dense, cold air above it. The portion of vehicle fuel that can be lost to rolling resistance is illustrated in green in Figure 4.3, which shows the fuel use breakdown of a 40 ton truck on typical road at highway speed along with that of a passenger car (Graedel and Allenby 1997; Sandberg September 2001).
Figure 4.3 - Fuel use breakdown of a passenger car and truck traveling on a highway.

While this is representative of one set of conditions, fuel consumption varies according to many factors; road grade, vehicle speed, vehicle weight and weight distribution are the most important factors since they influence the magnitude of the fuel lost to rolling resistance, air resistance, and gravitational resistance.

There are many studies that have attempted to quantify the impact of pavement structural properties on vehicle fuel consumption, but these have largely focused on the difference in that regard between flexible and rigid pavement types (Zanieowski 1989; NRC 2006; Sumitsawan et al. 2009). Because the proportion of fuel that is consumed due to this effect alone is widely variable in the literature, and because of the many complicating variables above, the magnitude of the effect has not been clearly established in such a way that can be generalized to all pavements and therefore represents a large gap in the data for a pavement LCA. A theoretical approach and experimental design is being developed which intends to reliably quantify this effect, and will potentially have a significant
impact in the life cycle assessment of pavements. Further discussion on the present modeling limitations of pavement-vehicle interaction effects are in Section 7.3.3. For more information, see MIT Master’s thesis by Mehdi Akbarian, which is expected to be published in Fall 2011.

4.6.4 Pavement Roughness

Surface roughness is an effect of wear accumulated on the road surface that increases fuel consumption of vehicles. This includes both unevenness of the road, and megatexture, as the finer textures (macrotexture and microtexture) have little effect on fuel consumption (Santero and Horvath 2009). Pavement roughness is typically measured through the International Roughness Index (IRI) in units of slope: in/mile or m/km. Because of different test vehicles and pavement conditions, there is not close agreement about the effect of surface roughness in the literature, and the values range from about 2-12% increase in fuel consumption when comparing a “rough” to a “smooth” surface. Error! reference source not found. presents results of all studies that have been performed with regard to the interaction of pavement roughness and fuel consumption.

<table>
<thead>
<tr>
<th>Study:</th>
<th>Sponsor</th>
<th>Year</th>
<th>IRI Value (m/km)</th>
<th>Increased Fuel Consumption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descornet (All)</td>
<td>ASTM</td>
<td>1990</td>
<td>Worst - Best</td>
<td>9</td>
</tr>
<tr>
<td>Laganier &amp; Lucas (Cars)</td>
<td>ASTM</td>
<td>1990</td>
<td>Worst - Best</td>
<td>6</td>
</tr>
<tr>
<td>Sandberg (Cars)</td>
<td>ASTM</td>
<td>1990</td>
<td>Worst - Best</td>
<td>12</td>
</tr>
<tr>
<td>Du Plessis (Trucks)</td>
<td>ASTM</td>
<td>1990</td>
<td>1.5-6.2</td>
<td>6.8</td>
</tr>
<tr>
<td>Du Plessis (Cars)</td>
<td>ASTM</td>
<td>1990</td>
<td>1.2-6.2</td>
<td>5.1</td>
</tr>
<tr>
<td>FHWA (Trucks)</td>
<td>FHWA</td>
<td>2004</td>
<td>1.2-2.4</td>
<td>4.5</td>
</tr>
<tr>
<td>NCAT (All)</td>
<td>Asphalt Industry</td>
<td>2004</td>
<td>1.08-1.18</td>
<td>2</td>
</tr>
<tr>
<td>U N. Florida (per 10% increase in IRI)</td>
<td>Independent</td>
<td>2007</td>
<td>-</td>
<td>1.3</td>
</tr>
<tr>
<td>Zaabar and Chatti (All)</td>
<td>Independent</td>
<td>2010</td>
<td>4</td>
<td>2.8-4.2</td>
</tr>
</tbody>
</table>

Table 4.3 - Effect of pavement roughness of fuel consumption of vehicles documented by different studies
Although the experimentally confirmed effect varies amongst the studies because of different test conditions, the data agree that within the present range of experimental conditions, there is a roughly linear correlation between an increase in IRI and an increase in fuel consumption. As such, the most recent study from Zaabar and Chatti (2011) is employed here to estimate the impact of pavement roughness on fuel consumption, as it differentiates between the effect on different vehicles. The present study applies Zaabar and Chatti’s value for “medium cars” to passenger car traffic (4.2% increase in fuel consumption per increase in IRI by 4 m/km), and the value for “articulated trucks” to truck traffic (2.8% increase in fuel consumption per increase in IRI by 4 m/km).

### 4.6.5 Predicting Pavement Roughness with MEPDG

The *Mechanistic-Empirical Pavement Design Guide* (MEPDG) software is used to predict pavement roughness during the 40 year analysis period, including the rehabilitative diamond grinding and slab repair that keep the pavement smooth. This tool was developed under the National Cooperative Highway Research Program (NCHRP) to expand beyond the purely mechanistic approach of the AASHTO design procedure (NCHRP 2004). MEPDG incorporates empirical data of pavement performance for different designs and circumstances in order to better predict performance. As part of its predictive capacity, the software can simulate several types of pavement degradation for different designs as well as in different climates (NCHRP 2004). The degradation over time predictions include cracked slabs (by percentage), faulting depth (in inches), and pavement roughness (using IRI, in in/mile). The IRI value is used to calculate fuel consumption. IRI predictions for the 40 year period are presented below in Figure 4.4 for three of the present urban functional classes: a high traffic structure (Interstate), a moderate traffic volume structure (Other Principal Arterial), and a low traffic volume structure.
Collector. These are each simulated in two different climates to show the impact of climatic conditions: a temperate (dry, non-freeze) climate in Oxnard, CA and an extreme (wet, freeze) climate in Rochester, MN.

Figure 4.4 - MEPDG-predicted roughness over 40 years for three functional classes in two climates.

In the case of all three functional types represented, the roughness of the pavement over time is highly sensitive to the climate conditions. This is due to freeze-thaw cycles, precipitation, and other weather patterns that are not found in temperate climate regions. The “urban collector” class becomes rough more quickly than the other road classes in both climate zones. This class experiences pronounced cracking and faulting in the MEPDG simulation, because it is the only one of the three without dowels to support vehicle load transfer between slabs.
An average is taken of the IRI values for the temperate and extreme climates as representative of each functional class for the present study. Because MEPDG does not allow for designing slab depths less than 6”, the following designs had more than a 1” difference between the design derived from the AASHTO procedure and the design simulated in MEPDG: rural minor collectors and local roads, and urban local roads. Since the life cycle impact from pavement roughness is on a per vehicle basis, this assumption should not have a significant effect on the overall life cycle impact for these structures since they have low traffic volumes, so the contribution from pavement roughness is low. The MEPDG-predicted values used for each functional class are listed for key years in Appendix 3.

**4.6.6 Traffic Delay**

Traffic delay that occurs during pavement construction, maintenance, and rehabilitation activities over the lifetime of the pavement is potentially one of the most significant contributions of life cycle greenhouse gases due to the additional fuel consumed by vehicles during the delays (Santero and Horvath 2009). This is especially true on roads with consistently high traffic volume, but the actual emissions depend on many parameters specific to the site and pavement project. Computationally, this is one of the most difficult life cycle components to model for an “average” pavement: first, because of the wide variety of construction work zone practices—including lane closures at different time intervals (nighttime, daytime, continuous, weekend, etc.), and full road closures rerouting traffic via detours—and secondly, because of complicated traffic dynamics that involve reduced speeds, deceleration/acceleration, and traffic queuing.
Models have however been developed in the field of life cycle cost assessment (LCCA) to estimate the user costs of different types of traffic delays. In the present study, a software tool developed by the Federal Highway Administration, called RealCost 2.5, is used to estimate the user costs for the representative pavements. From this cost information, vehicle delay in hours can be back-calculated based on the assumed value of time employed in the tool. Finally, the vehicle delay corresponds to a differential fuel consumption compared to when traffic is free flowing, and it is this additional fuel that is attributed to the life cycle. First the RealCost model will be presented, along with the assumed input values to represent the present scenarios, then finally the calculation method to estimate the greenhouse gas emissions associated with traffic delay.

RealCost 2.5

RealCost is an Excel spreadsheet-based calculation tool equipped with VisualBasic-coded macros which was developed by the Federal Highway Administration to evaluate long-term investment costs from construction alternatives that are born by different parties—including construction costs, agency maintenance and rehabilitation costs, and user costs (time and vehicle costs) (CALTRANS 2007). Because the life cycle impacts for the construction and rehabilitation activities are already otherwise accounted for in this study, only RealCost’s user costs during lane closures are relevant. These user costs arise when construction work zones restrict or divert the normal flow of traffic by producing vehicle queues or detours. RealCost estimates these costs based on the normal number of lanes and traffic volume, speed and composition, as well as the number of life cycle closures, the closure type, and closure duration. The resulting user costs are calculated due to vehicle slowdown, stop-and-go traffic through the queue, and reduced speed through the work zone.
The Caltrans *Life-Cycle Cost Analysis Procedures Manual* provides guidance on deriving input parameters for the *RealCost* simulations which were based on information on the structures presented in Chapter 3 of this thesis. Following this guidance, the input parameters for all 12 structures are documented in Appendix 2. A minimum recommended speed zone size with a buffer of ½ mile on either side of the work zone (NDOR 2002). Standard operating speeds were based on a design speed survey of state departments of transportation for all functional classes except minor arterials (Faghri et al. 2004). Minor arterial operating speeds are from Vermont State Design Standards based on the same FHWA classification (VTrans 1997). All other parameters were based on guidance from the manual.

Since the traffic delay is modeled in *RealCost* in terms of the number of lanes remaining open in each direction during the road work, it is not capable of simulating a singular lane closure on a two lane roadway, as with using flaggers to alternate bidirectional traffic flow through the remaining open lane. This would inevitably generate alternating queues in both directions, but the best that can be done within RealCost is to specify some fraction lanes remaining open in each direction (assumed for this analysis to be 0.5), which effectively squeezes the free flow capacity in each direction. The present study does not consider work zone management techniques such as flagging as described, detours, or building temporary lanes to reroute traffic, but it does estimate the impact of closing a portion of the roadway, which serves for the present purpose.

In order to determine the delay associated with various lane closure management options, the following three scenarios were evaluated: continuous 24-hour closures, 10-hour closures during peak low traffic (nighttime closure), and 10-hour closures during peak high traffic (daytime closure). In the cases where traffic is able to flow through the work zone unimpeded, and no queue forms, a daytime closure is assumed to be the typical practice, as this corresponds closely to the normal workday. In
cases where a queue forms during the day, nighttime closures are used as representative of standard practice. This is corroborated by policies in many state transportation agencies that actually restrict lane closures during peak hours for lane capacity traffic volumes above a certain threshold. Within this study, the cases in which queues form are urban interstates and urban expressways and other freeways, which both have lane capacities of 2299 vehicles per hour per lane (vphpl). Many states set the threshold for allowing lane closures to be below this level: 1800 vphpl (Mn/DOT), 1500 vphpl (WisDOT), 1600 vphpl (CDOT), 1430 vphpl (MoDOT), and 1490 vphpl (ODOT) are some examples. The implication is that daytime or continuous closure would be prohibited on these two road classes, as modeled here (Maze and Wiegand 2007). It is important to recognize that oftentimes lane closures cannot be avoided, because of budgetary and site-specific constraints, as well as emergency closures, but that the estimates here are meant to represent typical circumstances. To account for some variability, the work zone duration is estimated to fluctuate by a standard deviation of 25%, which represents unforeseen fluctuation in productivity at the jobsite.

For a discussion on the limitations of the traffic delay modeling approach, see section 7.3.3.

**Calculating Fuel Consumption from Traffic Delay**

In its calculation engine, RealCost uses the user delay in hours for each vehicle type (passenger vehicles, single unit trucks, and combination trucks) multiplied by a value of time factor for each vehicle type, and sums them together to obtain total user costs. Based on these assumed value of time factors, the duration of the delay is back-calculated for each vehicle type. It is this additional time that is converted into fuel consumed (gasoline for passenger cars, and diesel fuel for trucks), which are then
integrated into the life cycle model as a contribution to the GHG emissions. The formulae for estimating these quantities of fuel are described below:

\[ V_{\text{gas}} = \left( \frac{C_{\text{user}}}{VT_{\text{car}} \times p_{\text{car}} + VT_{\text{su}} \times p_{\text{su}} + VT_{\text{comb}} \times p_{\text{comb}}} \right) \times \left( v_{WZ} \times \Delta g_{\text{car}} \times p_{\text{car}} \right) \]

\[ V_{\text{diesel}} = \left( \frac{C_{\text{user}}}{VT_{\text{car}} \times p_{\text{car}} + VT_{\text{su}} \times p_{\text{su}} + VT_{\text{ct}} \times p_{\text{ct}}} \right) \times \left[ \left( v_{WZ} \times \Delta d_{\text{su}} \times p_{\text{su}} \right) + \left( v_{WZ} \times \Delta d_{\text{ct}} \times p_{\text{ct}} \right) \right] \]

Where

- \( V_{\text{gas}} \) = volume of gasoline consumed due to traffic delay (L)
- \( V_{\text{diesel}} \) = volume of diesel fuel consumed due to traffic delay (L)
- \( C_{\text{user}} \) = user costs ($)
- \( VT_{\text{car}} \) = value of time for cars ($/hr)
- \( p_{\text{car}} \) = traffic composed of passenger cars (%)
- \( VT_{\text{su}} \) = value of time for single unit trucks ($/hr)
- \( p_{\text{su}} \) = traffic composed of single unit trucks (%)
- \( VT_{\text{ct}} \) = value of time for combination trucks ($/hr)
- \( p_{\text{ct}} \) = traffic composed of combination trucks (%)
- \( v_{WZ} \) = average speed through the work zone (km/hr)
- \( \Delta g_{\text{car}} \) = loss of gasoline during congested traffic for cars (L/km)
- \( \Delta d_{\text{su}} \) = loss of diesel fuel during congested traffic for single unit trucks (L/km)
- \( \Delta d_{\text{ct}} \) = loss of diesel fuel during congested traffic for combination trucks (L/km)

This formula was applied to the matrix of results from RealCost which are in Appendix 2.

4.6.9 Pavement Lighting

Another life cycle component impacting the energy demand of a pavement providing safe driving conditions at night is pavement lighting. This involves installing properly spaced lamps along the roadway, as well as the luminaries and ballasts that house them, poles to support them, and cabinets to service their electrification. Only the operation of the lamps is included in the present analysis, as the capital goods are assumed to be a small portion of the life cycle impact for lighting, and therefore negligible to the life cycle impact of pavements. Lighting practices vary significantly according to many
different conditions: population density (urban/rural), constraints of the urban and natural terrain, access to electrification, and the controlling agency’s practices. However, lighting requirements are specified by AASHTO, which have been adopted as direct requirements in many state agencies or as a basis for creating their unique policy (AASHTO 2005). They thereby serve the present purpose of establishing a benchmark for the life cycle footprint.

The level of provision of roadway lighting is typically measured in average maintained illuminance during operation, as measured in lux. AASHTO’s recommended range of values for a roadway varies according to three parameters: pavement classification by color, roadway classification, and zoning (commercial, intermediate, or residential). These values for pavement lighting class R1 (which completely includes all concrete pavements) are presented in Table 4.4.

<table>
<thead>
<tr>
<th>Roadway</th>
<th>Zone</th>
<th>Average Maintained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstates</td>
<td>Commercial</td>
<td>8 to 12</td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
<td>8 to 10</td>
</tr>
<tr>
<td></td>
<td>Residential</td>
<td>6 to 8</td>
</tr>
<tr>
<td>Other Freeways</td>
<td>Commercial</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Residential</td>
<td>6</td>
</tr>
<tr>
<td>Other Principal Arterials</td>
<td>Commercial</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Residential</td>
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</tr>
<tr>
<td>Minor Arterials</td>
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<tr>
<td></td>
<td>Intermediate</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Residential</td>
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<tr>
<td>Collectors</td>
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<td></td>
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<td></td>
<td>Residential</td>
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<tr>
<td>Local Roads</td>
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</tr>
<tr>
<td></td>
<td>Intermediate</td>
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</tr>
<tr>
<td></td>
<td>Residential</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 4.4 - Illumination requirements in lux for concrete pavements by functional system (AASHTO 2005).
These illumination values can be achieved through designing the appropriate luminary spacing and lamp efficacy. The lighting calculations are based on the standard AASHTO luminary spacing distances, and a lamp efficacy of 100 lumens/Watt, which is an intermediate efficacy value, and is within the expected range of three of the most common lamp types (metal halide, high pressure sodium, and low pressure sodium). See Table 4.5 below for the approximate efficacy of different lamps for pavement lighting.

<table>
<thead>
<tr>
<th>Type of Light</th>
<th>Approximate Efficacy (lumens/Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Mercury</td>
<td>37-57</td>
</tr>
<tr>
<td>Phosphor-coated Mercury</td>
<td>40-63</td>
</tr>
<tr>
<td>Metal Halide</td>
<td>85-100</td>
</tr>
<tr>
<td>High Pressure Sodium</td>
<td>95-140</td>
</tr>
<tr>
<td>Low Pressure Sodium</td>
<td>100-183</td>
</tr>
<tr>
<td>QL Induction Lighting</td>
<td>67-74</td>
</tr>
</tbody>
</table>

Table 4.5 - Technological efficacy of different lamps for pavement lighting (Mn/DOT 2003).

Below is the calculation of the electricity demand for lighting (adapted from Santero (2009)):

\[
\text{Electricity Demand (kWh)} = \frac{M I_{avg} \times A \times t}{\varepsilon}
\]

Where
- \( M I_{avg} \) = average maintained illuminance (lux = lumens/m²)
- \( A \) = area (m²)
- \( t \) = total usage time (h)
- \( \varepsilon \) = technological efficacy (lumens/kW)

The total usage time is estimated to be 11 hours/day, or 160,600 hours for the 40 year period.
4.7 END OF LIFE RECYCLING AND DISPOSAL

At the end of the pavement’s life, pavements are assumed to be demolished and the materials are either recycled or landfilled. Concrete is widely recycled, at the rate of about 50% and rising in 1998, and the end uses of crushed concrete include as subbase material (68%), as aggregate in AC (9%), as aggregate in PCC (8%), as well as fill and other uses (Kelly 1998). Because crushing is required, no difference is noted between emissions of virgin and recycled aggregate for inclusion of these recycling practices in the model. Steel reinforcing bar is assumed to be recycled at the rate of 70% (USGS 2010).

<table>
<thead>
<tr>
<th>Life cycle component</th>
<th>Key factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rehabilitation</td>
<td>4% full depth repair and diamond grinding at years 20 and 30 1576 L diesel / lane-km per diamond grinding activity</td>
</tr>
<tr>
<td>Albedo</td>
<td>Radiative forcing component: 2.55 kg CO₂e / 0.01 decrease in albedo / m² Urban heat island component: 4.85 x 10⁻³ kg CO₂e / 0.01 decrease in albedo / m²</td>
</tr>
<tr>
<td>Carbonation</td>
<td>Carbonation depth: 8.5 mm</td>
</tr>
<tr>
<td>Pavement roughness</td>
<td>Cars: 4.2% increase in fuel / increase in IRI by 4 m/km Trucks: 2.8% increase in fuel / increase in IRI by 4 m/km</td>
</tr>
<tr>
<td>Traffic delay</td>
<td>10 hr daytime closure, 10 hr nighttime on urban interstate and other freeway Multi-lane: 1 lane closed each direction, 2-lane: 0.5 lane closed each direction</td>
</tr>
<tr>
<td>Pavement lighting</td>
<td>$\varepsilon = 100,000 \ \text{lumens/kW}; \text{MI}_{avg} = 9; 8; 9; 8; 6; 5 \ \text{Lux}; \ t = 160,600 \ \text{h}$</td>
</tr>
</tbody>
</table>

Table 4.6 - Summary of key input parameters for use phase components

4.8 CONCLUSION

In this chapter, the environmental impact modeling approach for concrete pavements is presented. First is a discussion of the life cycle modeling software, GaBi 4 (PE 2011). Second, the data sources, calculations, and assumptions that go into the model are presented in order to accurately include all materials and processes that are within the system boundary over the 40 year analysis period. For a discussion of the overall limitations of the LCA model and assumptions, see Section 7.3.3.
Section III: RESULTS

CHAPTER 5: LIFE CYCLE IMPACTS

5.1 INTRODUCTION

In this chapter of the thesis, the results from the modeling methodology outlined in Chapters 2-4 are presented. The results include an estimation of the life cycle global warming impacts of the 12 representative structures by pavement structure and life cycle component. Then a time series of emissions is shown for two of the structures in order to show the contribution for each year during the 40 year analysis. A sensitivity analysis is then presented to evaluate the variation in these results due to traffic volume, traffic delay, as well as numerous other pavement life cycle parameters. Finally, each representative structure is extrapolated onto its respective functional system in order to establish a nationwide footprint for new concrete pavements on an annual basis, as well as an estimate of cumulative emissions that are projected into the future.

5.2 IMPACTS OF 12 FUNCTIONAL SYSTEMS

The quantities of GHG emissions for the rural and urban pavement networks are presented separately in Figure 5.1 through Figure 5.4 on the following two pages. They are shown in absolute terms, and also by the percent contribution from each phase, and on the same vertical scales to ease comparison between the rural and urban networks. Since there is a negative contribution from carbonation, the totals for all pavements in Figure 5.1 and Figure 5.3 are the vertical extent minus the carbonation. It should be reiterated that these are representative of what is “normally” found to be true for each of these systems, and the variability is not shown, but will be presented in Section 5.4.
Benchmark GHG Emissions for 6 Rural Functional Systems

**Figure 5.1**

**Rural Concrete Pavements: GHG Emissions Per km by Functional System and by Life Cycle Component**

- Interstate
- Other Principal Arterial
- Minor Arterial
- Major Collector
- Minor Collector
- Local Road

**Figure 5.2**

**Rural Concrete Pavements: GHG Contribution by Functional System and by Life Cycle Component**

- Interstate
- Other Principal Arterial
- Minor Arterial
- Major Collector
- Minor Collector
- Local Road

[Legend for diagrams with bars and percentages]
Benchmark GHG Emissions for 6 Urban Functional Systems

Urban Concrete Pavements: GHG Emissions Per km by Functional System and by Life Cycle Component

Figure 5.3

Urban Concrete Pavements: GHG Contribution by Functional System and by Life Cycle Component

Figure 5.4
Total life cycle GHG emissions range from 404 metric tons CO$_2$e (rural “local road”) to 6500 metric tons CO$_2$e (urban “interstate”) per kilometer, varying by an order of magnitude. This is largely due to the fact that interstates are much more massive structures, both in terms of depth of the concrete slab, as well as the width across the road. For example, the representative rural “local road” is 4 in thick, with two lanes of 11 ft each, and two 2 ft shoulders, whereas the urban “interstate” has 12 in of concrete, has three 12 ft lanes in each direction, and two inner and two outer 10 ft shoulders. Traffic is the other primary driver of the variation across structures, which affects the fuel consumed due to roughness.

When looking at the life cycle GHG contributions for each road type, the first notable feature is that cement production emissions are the largest contribution for every one of the 12 structures, and therefore presents the largest opportunity for reducing life cycle emissions. The contribution of cement production ranges from 51% (for urban “interstate”) to 85% (for rural “local roads”) of the total life cycle emissions. The second largest contribution is “fuel consumed from roughness” in every case except for rural “major collector,” “minor collector,” and “local road,” and urban “local road,” where carbonation is the second largest contribution.

For numerical results for all functional systems, consult Appendix 4. For validation of these results as compared to other pavement LCA studies, see Section 7.2.1.
5.3 TIME SERIES EMISSIONS

While the majority of life cycle greenhouse gas emissions are due to initial production and construction at the beginning of the analysis period, there are several effects occurring continuously throughout the use phase (albedo, carbonation, fuel consumption due to roughness, and pavement lighting), and several one-time events after production (rehabilitation, traffic delay, and end of life demolition, transport, recycling and disposal). This is shown for the two cases of rural and urban “interstate” in Figure 5.5 and Figure 5.6.

The initial emissions in year one—from materials extraction, production, and pavement construction—dominate the time series of emissions, at 75% of the total contribution for the rural interstate and 62% for the urban interstate. The second largest one time contribution is from end of life demolition, transport, recycling and disposal, contributing 7% and 6% respectively. Carbonation is more active initially after new construction and each rehabilitation activity, and then the effect slows, while lighting has a continuous contribution throughout the 40 year period, and roughness related emissions increase up until diamond grinding occurs. GHG emissions from diamond grinding and traffic delay at each rehabilitation event contribute between 1-2% of life cycle emissions for both roads.
GHG Emissions Over 40 Year Analysis Period

Figure 5.5

Emissions Over Analysis Period for Rural Interstate Built in 2008

Production and construction (2774 Metric Tons CO$_2$e)

End of life demolition, recycling, and disposal

Carbonation (decreasing rate), Lighting (constant rate), and Fuel Cons. from Roughness (increasing rate)

Diamond grinding and traffic delay

Figure 5.6

Emissions Over Analysis Period for Rural Interstate Built in 2008

Production and construction (3828 Metric Tons CO$_2$e)

End of life demolition, recycling, and disposal

Carbonation (decreasing rate), Lighting (constant rate), and Fuel Cons. from Roughness (increasing rate)

Diamond grinding and traffic delay

Figure 5.5
5.4 SENSITIVITY ANALYSIS

One of the variables that the results are most sensitive to is the traffic volume that the pavement structure supports. Within each functional system, there is a large traffic variability, which is shown in Figure 3.2 in Chapter 3. The present benchmark only takes the average traffic as representative, when in reality the pavement thickness, number of lanes, width of shoulders, and fuel consumption due to roughness, all vary according to traffic volume. The derivation of representative high and low end structures using FHWA data on the traffic that is distributed on each functional system is explained in Chapter 4. The variability of GHG emissions in Figure 5.7 and Figure 5.8 below span between the first and fifth sextiles of AADT, which approximates one standard deviation from the mean. Some of the pavement networks stand out as particularly variable: rural interstate, and urban interstate, other freeway/expressway, other principal arterial, and minor arterial. This is partially because of large traffic variability on these networks, but also because the number of lanes in the representative structures changes, which accounts for the asymmetric skew in many of the error bars.
Sensitivity of Results to Traffic Volume for Rural and Urban Functional Systems

**Rural Network: Variability in GHG Emissions per km From Traffic Volume by Functional System**

![Graph showing GHG emissions for rural network by functional system](image)

**Urban Network: Variability in GHG Emissions per km From Traffic Volume by Functional System**

![Graph showing GHG emissions for urban network by functional system](image)

Figure 5.7

Figure 5.8
The results are also sensitive to lane closure timing and duration during new construction and rehabilitative activities. It is assumed here that the pavement construction is done in order to appropriately balance construction costs and user costs, and so traffic queues are avoided by closing lanes during the night rather than the day. But often, daytime closures are unavoidable and queues indeed form, because of emergencies, budgetary constraints, or other complicating factors. This can have a dramatic impact on the life cycle. Daytime closures are shown on the urban network below, where traffic queues account for a large majority of the traffic delay component. Queues do not form on any of the rural roads, and so the results do not vary significantly and are not shown.

Figure 5.9 - GHG Emissions occurring on the urban network due to 10 hour daytime closures.
On the urban interstate, consistently using daytime closures throughout the pavement life cycle results in an increase in emissions of about 2100 metric tons CO$_2$e, and comprises 26% of the total life cycle for this case. On the urban other freeway/expressway, the representative traffic level is squeezed from 4 lanes down to two lanes, and 8 km long queues are predicted by RealCost during peak daytime traffic, which contributes 6400 additional metric tons CO$_2$e to the life cycle, constituting 62% of total emissions.

5.4.1 Overall Sensitivity

Based on variability in the input parameters that was specified in the Methodology of Section II, the sensitivity of the results to this variability is presented below. Certain parameters have a greater bearing on the sensitivity of the results, but the importance of each parameter also depends heavily on the functional system of concern. For example, the variable influence of climatic zone on pavement roughness is likely important to the total life cycle emissions on a high traffic volume urban interstate, but not so on a local road where fuel consumed due to roughness has a small life cycle contribution.

In the following sensitivity checks the traffic volume parameter was held fixed because of its heavy influence on the pavement design—the AASHTO design equations depend heavily on expected traffic volume and traffic composition. These equations are not, however, operational in the GaBi model and the structures are input separately from the design procedure outlined in Chapter 3. Hence the sensitivity to traffic was analyzed separately above. Concrete depth and number of lanes were additionally not varied, as they generally depend on traffic volume. These important parameters are also included in the above section.
The sensitivity analysis results are presented separately for the rural and urban networks below in Figure 5.10 and Figure 5.11. The graph shows the sensitivity of the overall results to a variation by one standard deviation away from the nominal value that is normally used to calculate the results. Only those parameters which exceeded a 2% effect on a majority of the functional systems were included in the results. They are sorted according to rural “minor arterials” and urban “other principal arterials” from most influential parameter (at top) to least influential parameter (at bottom) according. The parameter names, their nominal value, and their standard deviation are presented in Table 5.1.

It can be seen that the results become more sensitive to certain parameters as one moves from smaller to larger roads (such as change in IRI over the first 20 years), while other parameters are more important on the smaller roads (such as outer shoulder width, carbonation rate, pavement albedo, etc.). This is primarily due to the fact that the parameters to which the results are more sensitive correspond to life cycle components that contribute a larger proportion of the overall emissions. In general, smaller roads are more sensitive to parameters which relate to the materials production, since this has a larger overall contribution to the total. They are also sensitive, however, to use phase components that are driven by surface area, like carbonation and pavement albedo. Larger roads are more sensitive to traffic-related parameters, since the roughness and traffic delay components comprise a larger proportion of the overall emissions. There are also variations across the functional systems that are due to different nominal values in the parameters themselves across the roads, as in the case with number and width of lanes, number and width of shoulders, lighting requirements, and roughness.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Nominal Value</th>
<th>St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Depth</td>
<td>18.4 cm</td>
<td>10%</td>
</tr>
<tr>
<td>Pavement Albedo</td>
<td>0.325 (unitless)</td>
<td>8%</td>
</tr>
<tr>
<td>Outer Shoulder Width</td>
<td>In Figure 3.3</td>
<td>33%</td>
</tr>
<tr>
<td>Lane Width</td>
<td>In Figure 3.3</td>
<td>9%</td>
</tr>
<tr>
<td>IRI @ 20 Years</td>
<td>In Appendix 3</td>
<td>11%</td>
</tr>
<tr>
<td>Car Fuel Inc. from IRI</td>
<td>1.05%/1 m/km</td>
<td>25%</td>
</tr>
<tr>
<td>Carbonation Depth</td>
<td>8.5 mm</td>
<td>50%</td>
</tr>
<tr>
<td>Cement % In Mix</td>
<td>13.7%</td>
<td>8%</td>
</tr>
<tr>
<td>Agg. % by Rail</td>
<td>27%</td>
<td>93%</td>
</tr>
<tr>
<td>Agg. Truck Dist.</td>
<td>50.3 km</td>
<td>24%</td>
</tr>
<tr>
<td># Rehab. Events</td>
<td>2</td>
<td>22%</td>
</tr>
<tr>
<td>Rehab Patching %</td>
<td>4%</td>
<td>19%</td>
</tr>
</tbody>
</table>

Table 5.1 - Most influential model parameters
Sensitivity of Results to Model Parameters on Rural and Urban Networks

Figure 5.10 - Sensitivity of overall results to 12 most influential parameters on rural network.

Figure 5.11 - Sensitivity of overall results to 12 most influential parameters on urban network.
5.5 EXTRAPOLATION TO ENTIRE NETWORK

Following the procedure outlined at the end of Chapter 3, the benchmark results representing each of 12 functional systems were extrapolated based on the number of lane-miles of that system in order to obtain a national benchmark for the annual greenhouse gas emissions due to new concrete pavement construction. Figure 5.12 shows the number of miles for each of the five primary systems, as well as the growth over time. During this period, rural roads constitute approximately 43% of the entire network by length, and urban roads 57%. Adjusting for the frequency of each functional system, as well as adjustments for lane counts and lane widths (per the method described in Chapter 4), the results in Figure 5.13 below represent the carbon footprint of all new concrete roads built annually on average during 1999-2008.

These emissions total 2.6 Tg (million metric tons) CO$_2$e per year, or approximately 0.03% of US annual GHG emissions according to the 2009 EPA GHG Inventory (EPA 2009). This is on par with GHG
emissions from the petrochemical industry (2.7 Tg CO$_2$e) or the aluminum industry (3.0 Tg CO$_2$e) in terms of direct smokestack emissions. This is equivalent to annual emissions from about 500,000 operating passenger vehicles, or 0.6 coal-fired power plants (EPA 2011). This is a small proportion of overall GHG emissions in the US, but does not account for a large proportion of the pavement network (namely asphalt or asphalt rehabilitation on concrete pavements), nor the life cycle impacts of vehicle and goods damage, nor the potential impact of consequential effects of construction such as induced road transport traffic.

Figure 5.13 - Average annual life cycle GHG emissions from new concrete pavements in US by functional system
In sum, the rural network contributes 1.2 Tg CO$_2$e per year (47% of total), and the urban network contributes 1.4 Tg CO$_2$e per year (53% of total). Urban interstates contribute 0.5 Tg CO$_2$e per year (19% of total), because of the massive structures and large proportion of concrete relative to asphalt. Collector roads on both rural and urban networks have the smallest contribution to the national emissions, and this is because this functional system has grown almost negligibly from 1999-2008, at an average of 0.03% per year.

Projecting these annual emissions 40 years into the future based on the average annual growth rate in the concrete pavement network for 1999-2008, the cumulative GHG are predicted in Figure 5.14. The first notable feature is that the accumulation of emissions are constant, because the average growth rate for each road is assumed to be constant into the future. A discussion of the sensitivity to the pavement network growth rate is below in Section 7.2.4. It can also be seen that “Interstates and other freeways” (which combine urban and rural “interstates” with urban “other freeways and expressways”) represents the largest proportion of these emissions. These projections set a benchmark which allows comparison with potential reduction strategies that can be implemented into the future, which are shown evaluated by comparison to this benchmark in Chapter 6. For validation of the extrapolation procedure and results, see Section 7.2.2.
5.6 CONCLUSION

In this chapter of the thesis, the results of the pavement LCA are presented, which include: 1) an analysis of the 12 representative structures, 2) a time series of emissions during the 40 year analysis, 3) a sensitivity analysis is then presented to evaluate the variation in these results to variation, and 4) a nationwide footprint for new concrete pavements on an annual basis for 2008 and projected up to 2050. The life cycle greenhouse gas emissions for all new concrete pavements constructed in the US is approximately 2.6 Tg CO$_2$e per year, or about 0.03% of total emissions in 2009. For discussion of the limitations of this chapter, see Sections 7.2.2 through 7.2.4.
CHAPTER 6: REDUCTION OPPORTUNITIES

6.1 INTRODUCTION

This chapter considers five strategies that have significant potential to reduce life cycle GHG emissions of concrete pavements: 1) fly ash replacement, 2) whitened aggregate, 3) increasing carbonation through end-of-life management, 4) reducing fuel consumption due to pavement roughness through additional pavement rehabilitation, and 5) a combination of all four of these scenarios. The chapter consists of two parts: the first presents the methodology for quantifying the GHG reduction strategies and its accompanying assumptions, and the second part presents the numerical results for the GHG reduction scenarios as compared to the baselines that were established above in Chapter 5.

6.2 EVALUATION METHODOLOGY

Once there is a benchmark in place for the life cycle carbon footprint of different pavement types, this information can be used to identify opportunities for reducing the life cycle carbon emissions, as well as provide a baseline for comparison. In the following section six GHG reduction scenarios are considered. These are a combination of strategies to a) reduce the cement content, which contributes between 51% (on urban interstates) and 85% (on rural local roads) of total GHG emissions, and b) to reduce use phase emissions that have large potential according to the results of section 5.2 and the sensitivity analysis of section 5.4. These are: cement replacement with coal fly ash, increasing albedo with white aggregates, increasing carbonation through end-of-life waste concrete management,
reducing fuel consumption by diamond grinding the pavement more often, and finally a scenario that combines all of these reduction strategies in order to see what reductions are achievable. These strategies are not meant to be an entirely exhaustive set of carbon reduction strategies for concrete pavements, but are an exploratory set of strategies that represent options for reducing the carbon footprint. Table 6.1 includes a summary of the key parameters and assumptions that are employed here.

### 6.2.1 Fly Ash Replacement

Intended as a cement-content reduction strategy, fly ash substitution represents a significant potential in the United States. It should be noted that there are other strategies to reduce cement content, such as design mix optimization, the use of other substitutes such as blast iron slag, amongst other strategies.

In order to evaluate the potential for GHG reduction through fly ash substitution in the raw meal, a reduction in CO₂ emissions of 30% for the average blended cement was applied (Worrell et al. 2000). Several agencies allow for up to 30% replacement of cement with fly ash (ACPA 2011).

Partial substitution of cement with fly ash has been shown experimentally to increase the carbonation coefficient (the rate of carbonation) and the carbonation depth (Papadakis 2000; Khunthongkeaw et al. 2006). At 30% fly ash replacement, the carbonation depth increases from 8.5 mm to between 12 and 16 mm (Papadakis 2000). An average of 14 mm was assumed here to estimate the increased carbonation over the 40 year pavement life.
It should also be noted that an increased carbonation depth correlates strongly to a decrease in compressive strength. The influence of increased carbonation on pavement durability was not explored in the present study and is an area for future investigation.

### 6.2.2 Increasing Pavement Albedo

In order to estimate the reduction opportunity that constructing a whitened pavement presents—both in terms of reduced pavement lighting demands, and in terms of the albedo effect (see Section 4.6)—a linear extrapolation of the pavement albedo’s relationship to lighting demand was derived to estimate the lighting needs on whitened pavement. This was based on extrapolating AASHTO average maintained illuminance recommendations for asphalt and concrete, and an assumed average albedo of 0.1 and 0.325, respectively (Pomerantz and Akbari 1998). According to tests by Levinson and Akbari 2002, the highest albedo (or brightest) concrete pavement that they were able to engineer only based on selecting appropriate fine and course aggregates had an albedo of 0.52, and 0.41 after being formed at week 69. This was achieved with a combination of beach sand (albedo of 0.45) and plagioclase rock (albedo of 0.49), which are pictured in Figure 6.1 below. The extrapolated illumination requirements are 9 for interstates, 6.5 for other freeways, 6.5 for other principal arterials, 6.9 for minor arterials, 4.9 for collectors, and 4.2 for local roads.

![Figure 6.1 - White aggregates used to increase pavement albedo.](image)
The albedo effect of the whitened pavement scenario was measured with reference to the average concrete albedo (0.325), so anything with higher albedo is attributed with negative life cycle emissions. Emission factors for the albedo effect are given in Chapter 4.

6.2.3 End-of-Life Carbonation

Once a pavement is demolished at the end of its life, it often goes through a jaw crusher for downcycling as subbase, fill, or concrete aggregate. Once it is crushed to a grade of 17 mm—which corresponds to a medium grade aggregate—the exposed surface area increases dramatically, and the carbonation depth no longer becomes a limiting factor. If this crushed concrete is left to sit for 50 years, it can achieve a carbonation depth of 8.5 mm, which would saturate the aggregate’s ability to carbonate (Santerno and Horvath 2009). The maximum theoretical limit for carbonation is 75% of the original CO2 that was emitted during calcination of cement during cement production. This value is assumed here to show what can be achieved through proper end-of-life management of concrete pavement, which corresponds to 75% of 553 g of CO2 per 1 kg of cement in the mix (Marceau et al. 2006). Despite carbonation’s effect on reducing compressive strength, durability issues were not accounted for here. This is a potentially important issue in the life cycle and is an area identified for future research.

6.2.4 Fuel Consumption From Roughness

Additional fuel consumed by vehicles driving on rough pavements can be partially mitigated by proper maintenance and more frequent rehabilitation of the pavement surface. This is evaluated by adding an additional pavement rehabilitation at year 10. This consumes additional energy from
diamond grinding, and requires that the structure is 1 cm thicker at the initial construction in order to make a more accurate comparison between the life cycle of this scenario and the baseline scenario (WSDOT 2011). The additional activity benefits the life cycle in two ways: firstly, the pavement roughness is brought back down to the initial IRI of 63 m/km, and secondly, completely uncarbonated concrete is exposed to the environment and carbonation resumes again at a faster rate as per Fick’s second law of diffusion (Santero and Horvath 2009).

6.2.5 Carbon-Optimized Concrete Pavement

This reduction strategy incorporates all of the above scenarios, with the exception of the additional rehabilitation for rural “major collector,” “minor collector,” “local road,” and urban “local road” because these obtained no life cycle carbon benefit. Rather than merely summing the benefit from each strategy, this is done so as to intentionally capture the interactions between each of these strategies. For example, while the fly ash strategy alone has an increased carbonation rate due to the fly ash, this increase was not assumed while the pavement is in situ for the combined scenario because the end-of-life carbonation scenario already assumes the theoretical maximum carbonation rate.

<table>
<thead>
<tr>
<th>Reduction Scenario</th>
<th>Key factor / Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly ash substitution</td>
<td>30% replacement of cement; 14 mm carbonation depth</td>
</tr>
<tr>
<td>White aggregate</td>
<td>Concrete $\alpha = 0.41$; MI$_{\text{avg}} = 9$; 6.5; 6.9; 4.9; 4.2</td>
</tr>
<tr>
<td>End-of-Life Carbonation</td>
<td>415 g CO$_2$ / kg cement sequestered over analysis period</td>
</tr>
<tr>
<td>Additional rehabilitation</td>
<td>Diamond grinding of 1 cm at year 10, 1 cm increased initial pavement depth</td>
</tr>
<tr>
<td>Combined scenario</td>
<td>No additional rehabilitation on rural major and minor collector and local road, and urban local road. Carbonation saturates at 75% of calcination CO$_2$,</td>
</tr>
</tbody>
</table>

Table 6.1 – Summary of key input parameters for reduction scenario analysis
6.3 RESULTS

These carbon reduction strategies were first applied to the project-level structures on a per kilometer basis in order to give agencies that are in control of these functional types of roads explicit recommendations for how to design less GHG-intensive concrete pavements. The strategies were then applied to the entire network in order to show the carbon reductions that are achievable through national policy. The project-level reduction scenarios are displayed in Figure 6.3 and Figure 6.2.
GHG Emissions per km from Reduction Strategies by Functional System

Rural Network Opportunities: GHG Emissions Per km by Functional System and by GHG Reduction Strategy

![Graph showing GHG emissions by different strategies and functional systems for rural networks.]

Figure 6.3

Urban Network Opportunities: GHG Emissions Per km by Functional System and by GHG Reduction Strategy

![Graph showing GHG emissions by different strategies and functional systems for urban networks.]

Figure 6.2
The most effective reduction strategy depends on the functional system of concern. On Interstates, end-of-Life carbonation is the most effective strategy, whereas fly ash substitution wins out (albeit narrowly) on all structures with an AADT of less than 20,000 vehicles/day. There is the exception of rural local roads, which are thin enough that the surface area to volume ratio encourages an albedo reduction strategy (which is dependent on surface area) over fly ash substitution (which is volume related).

Increasing pavement albedo through obtaining a white aggregate supply reduces life cycle equivalent carbon emissions by 9% of the total on urban interstates (529 metric tons of CO$_2$e) and up to 48% of the total on rural local roads (153 metric tons of CO$_2$e). From a carbon-management perspective, sourcing lighter colored aggregates may require trading off with a longer aggregate transportation distance. Since the life cycle benefit varies across each road, the willingness to trade-off with increased aggregate transportation also varies. White aggregate (of albedo 0.45-0.49) gives a net life cycle carbon benefit for an urban interstates at transport distances up to 200 km by truck, 1100 km by barge, or 1700 km by rail. For a rural local road, there is a benefit up to about 850 km by truck, 3800 km by barge, and 8200 km by rail. This point is however sensitive to the durability of the pavement as well as the analysis period.

The additional pavement rehabilitation scenario only benefits some roads, primarily because of the additional emissions from each rehabilitation activity is greater than the emissions saved by way of fuel consumption due to roughness. Whereas a 14% reduction in GHG emissions occurs on high traffic urban interstates, the life cycle carbon footprint of rural local roads increases by 7%. There is a crossover point where this strategy becomes beneficial at an AADT of greater than approximately 2500 vehicles/day.
Combining all four strategies, significant carbon reductions are obtained across all functional systems. In the case of urban interstates, a 58% GHG reduction is obtainable by combining the four strategies, which amounts to a reduction of 3500 metric tons CO₂e per kilometer, which is equivalent to taking 637 cars off the road for every kilometer of interstate that the combined strategy is applied to. This reductions achievable increase as traffic volume decreases—negative life cycle carbon emissions are achieved on the rural local road. In this case, carbon that is sequestered through carbonation and light that is reflected from pavement albedo outweigh combined emissions from all other life cycle phases. A discussion of the caveats that should come with the claim to be “carbon neutral” or “carbon negative” can be found in Section 7.3.4.

6.4 US NETWORK-WIDE GHG REDUCTION STRATEGIES

Extrapolating these scenarios appropriately across the entire US pavement network, the strategies can be evaluated for their potential to reduce GHG at the national level, which may have implications to national transportation infrastructure policy. In Figure 6.5 below, the annual benchmark carbon emissions for newly constructed concrete pavements in the US is shown, as well as the network-wide reductions that are achievable if these strategies are deployed ubiquitously.

For new concrete pavements, if all concrete paving ready mix producers were to incorporate 30% fly ash into their mix, 645,000 metric tons CO₂e would be avoided each year on average, which is equivalent to taking about 125,000 cars off the road, or avoiding emissions from 1.5 million barrels of oil. This is approximately equal in scale to end-of-life carbonation management, which avoids 630,000 metric tons CO₂e. Rehabilitating all roads additionally at year 10 has about one quarter the impact of
the former two strategies, avoiding 160,000 metric tons CO$_2$e nationally per year. Using white aggregate could save 470,000 metric tons CO$_2$e nationally.

Employing all four strategies on a network-wide basis reduces life cycle greenhouse gases of concrete pavements by 69%, saving 1.76 million metric tons CO2e annually. This is equivalent to taking 350,000 cars off the road, and the emissions from electricity to power about 150,000 homes for a year.

Figure 6.4 below shows cumulative greenhouse gas emissions projected until 2050. Cumulatively, optimizing concrete pavements with this strategy will save about 17 million metric tons CO$_2$e at the current rate of growth in new construction. This is equivalent to shutting down 1 coal fired power plant every 2.3 years.

There are negligible emissions on the “collectors” network, and this is because collectors have a near zero growth rate (0.03%).
GHG Reduction Strategies for US Concrete Pavements

**Figure 6.5**

Average Annual Life Cycle GHG Emissions From New Concrete Pavements in US

**Figure 6.4**

GHG Reduction Strategy Wedges
6.5 CONCLUSION

This chapter considers five strategies that have significant potential to reduce life cycle GHG emissions of concrete pavements. It first presents the methodology used to quantify the GHG reduction strategies, as well as accompanying assumptions, and then presents potential GHG reductions. By combining the four strategies, this leads to a GHG reduction potential of between 58 and 104% for the different functional systems on a per-kilometer basis, and 69% reduction when estimated for the entire extrapolated concrete pavement network. For further discussion on limitations of this chapter and the potential for future work, see Section 7.3.4.
SECTION IV: CONCLUSIONS

CHAPTER 7: KEY FINDINGS AND FUTURE WORK

7.1 INTRODUCTION

This chapter is divided into three parts. The first part evaluates these results by validating them as compared to other studies, both for the life cycle GHG estimated for the concrete pavement functional systems and for the national life cycle GHG emissions of the entire concrete pavement network. The second discusses the shortcomings of the thesis, and presents potential subsequent opportunities for future research in this domain. The third part presents a concise set of key findings of the thesis.

7.2 VALIDATION OF RESULTS

In this section, the results presented in Chapters 6 and 7 are compared with the findings from other studies in order to check the validity of these results. The LCA results of the project-level structures are compared with LCA studies of similar pavement structures and of similar scope of analysis. Then the results for the mass of the extrapolation of the functional class structures to the extent of the entire network are compared to a report accounting for concrete pavements constructed on an annual basis.
7.2.1 Validation of LCA Results

The present results can be compared to other pavement LCA studies in some instances, in order to provide a litmus test as to the accuracy of the present method. Comparing with most other studies, however, is extremely difficult because there is no standard method for conducting a pavement LCA, and because the goal and scope of each study is different. The primary parameters that vary across studies and thereby inhibit their comparison are as follows: system boundary definition, life cycle phase aggregation/differentiation, pavement geometry, analysis period, impact category, year, and region of analysis, amongst others. For example, two studies that analyze a 1 km length of concrete pavement estimate life cycle CO\textsubscript{2} (not CO\textsubscript{2}e) emissions that vary significantly: from 940 metric tons (Häkkinen and Mäkelä 1996) to 2750 metric tons (Stripple 2001), but one must verify the structures and assumptions that lead to these results in order to obtain a reliable comparison. In the case of the large discrepancy in results between these two studies, it is likely due to the inclusion of many activities during construction in Stripple 2001 that aren’t usually considered a part of the life cycle of the pavement alone. The construction phase extends back to clearing the roadway, hauling dirt for cuts-and-fills necessary to level the subgrade, and includes ancillary materials production and placement, such as fences and railings, road signs, and traffic lights, as well as maintenance of these material goods over the 40 year analysis period. None of these life cycle components are included in Häkkinen and Mäkelä (1996).

In the case of other reports, they do not document key assumptions and data such that an interpretation can be made about what is driving the contribution to the end result for the entire life cycle. This is a common problem in LCA, and one that the present study tries to avoid by clearly documenting all assumptions, as well as grouping the most critical parameters across multiple phases into tables.
Comparison with Milachowski et al (2010)

Milachowski et al (2010) is one of the most recently published pavement LCAs, and also the easiest to compare in terms of geometry and life cycle phases, because of thorough documentation that is lacking in other reports. It performs a comparative LCA of concrete and asphalt roads across five different impact categories, including global warming potential. The concrete structure analyzed has a concrete slab top course that is 10.6 in depth, which is on a thin geotextile interlayer, a 5.9 in hydraulic bond layer$^3$, and a 17 in layer of base. It has two lanes in each direction, with two total outer shoulders that are 9.8 feet in width. The structure being presently analyzed which corresponds most closely in terms of geometric dimensions is the urban “other freeway and expressway,” which has concrete slabs that are 11 in thick, have a 6 in base layer, two lanes in each direction, 2 outer shoulders that are 10 ft in width, and additionally has two inner shoulders which are 4 ft in width (Milachowski et al. 2010). The results for global warming potential (also per the CML method) for the production and construction phases range from 2150-2800 metric tons CO2e, depending on the concrete mix and recycled content of the base layer. This agrees well with the results for the urban “other freeway and expressway,” which when summing only the contributions from cradle-to-construction phases gives 2846 metric tons CO2e, which is 1.6% greater than their most GHG-intensive scenario, and 32% greater than their least GHG-intensive scenario.

A large portion of the above discrepancy likely comes from the additional 4 ft inner shoulders used in this study, which makes the concrete slabs 14% more voluminous. Adjusting the GWP results from Milachowski et al proportionally to the concrete slab volume, their impact range changes to 2451-3191 metric tons CO2e, with a midpoint of 2821 short tons CO2e—which differs negligibly from the 2846

$^3$ This is a cement-treated base with approximately 25% the quantity of cement per unit volume as compared to the wearing course layers used in the study.
metric tons CO\textsubscript{2}e from the present urban “other freeway and expressway.” The use phase elements in the \textit{Milachowski et al} study include large contributions from daily traffic congestion and vehicle wear-and-tear, which are not elements of the present study and thus not comparable. This does, however, instill confidence through the mutual validation of these two studies.

### 7.2.2 Validation of Extrapolation Procedure

As a validation for the extrapolation procedure, the mass of concrete derived by this process can be compared with a national concrete pavement accounting report produced by the Portland Cement Association for 2007 (PCA 2007). This report is a large inventory of every project bid by state DOTs collected by Oman Systems, Inc., and gives the total sales for the year by economic value (in dollars) and by volume (in cubic yards). Converted to m\textsuperscript{3}, a total of 7.12 million m\textsuperscript{3} are produced in 2007.

The extrapolation procedure is described in depth at the end of Chapter 3. In summary, the AASHTO structures that are representative of each functional system were adjusted to account for the average number of lanes on each functional system at the national level, as well as the median lane width. These adjusted structures were then multiplied by the length of new construction for each functional system annually. According to this method, an estimation 6.92 million m\textsuperscript{3} of new concrete pavement is produced in 2007, which agrees well with 7.12 million m\textsuperscript{3} from the PCA report, as it is within 3\% standard error.
7.2.3 Validation of National Footprint Results

An EPA report quantifies GHG emissions using a life cycle assessment approach to quantify emissions for 2006, as an alternative framing of GHG emissions as compared to their usual GHG inventory of direct emissions of each industry. It comprises a systems-based view of US GHG emissions, where “each system represents and comprises all the parts of the economy working to fulfill a particular need” (EPA 2009). Infrastructure is included as one of these systems, which is comprised of roads and water systems, which is estimated using the Economic Input-Output Life Cycle Assessment (EIO-LCA) approach to account for 72 Tg CO$_2$e in 2006. This is disaggregated into the road and water infrastructure components, which results in 56.9 Tg CO$_2$e for highway, street, bridge and tunnel construction. The proportion of paved kilometers in the US that are concrete as opposed to asphalt or composite pavements compose 6.0% of the total network in 2006 according to FHWA Table HM-12 for that year. Multiplying total GHG associated with roads by this proportion, an estimated 1.2 Tg CO$_2$e are from concrete. This is likely an underestimate, because concrete constitutes a much larger relative proportion of interstates (27%) and other high traffic volume roads, which are many times more massive than local roads. The EPA estimate, however, is on the same order of magnitude as the present estimate of 2.6 Tg CO2e, which is a re-extrapolation for the year 2006.

7.2.4 Sensitivity to Growth Rate

The growth rate of the network is a key parameter which dictates the amount of concrete constructed each year. In order to extrapolate growth into the future, large yearly fluctuations are removed by using a 10 year average for the growth rate. It is assumed that the growth in concrete is a fixed proportion of the growth of the entire network, which brings in additional uncertainty. Using the
network growth rate also ignores that some roads may be demolished and removed from the network, but this is assumed to be negligible.

While the growth rate is about 0.35% for the entire network from 1999 to 2008, this rate fluctuates historically as shown below in Figure 7.1.

![Average Growth Rate of All US Public Roads](image)

**Figure 7.1 - Average growth rate for the extent of US public roads from 1909-2008.**

It can be seen that the growth rate has fluctuated quite dramatically over the 90 year period, varying from as low as -0.1% to as high as 2.6%. There was a period of explosive growth during the early 1900’s, and then very low, and even negative, growth during the great depression era (circa 1929-1940’s). Growth of the network began to accelerate around the time of the Federal-Aid Highway Act of 1956, then remained somewhat steady around 0.5% growth until the oil crisis of 1979, which caused peaking gas and asphalt prices. The growth rate has steadily increased since the beginning of the 1990’s.
Road expansion does not only increase greenhouse gas emissions from the pavements alone, but it also has been shown to induce travel, contribute to urban sprawl, and increase reliance on vehicle transport thereby reducing usage of public transit and other less GHG-intensive forms (Anas and Timilsina 2009). These effects are not included in the present LCA.

### 7.3 LIMITATIONS AND FUTURE WORK

The present life cycle assessment method models a multi-tiered supply chain for a complex pavement network that has within it many different sources of regional, temporal, and technological variability. This undertaking inevitably involves many simplifying assumptions, which have been documented throughout this thesis. This allows the study to be reproducible, and allows for the reader to understand what the results are representative of. Just as it is important to be transparent about what the study represents, the limitations of the present work are conveyed here for clarity and completeness.

#### 7.3.1 Goal and Scope of LCA

Defining the goal of the LCA is an important framing step that enables the research to answer an important question, but at the same time constrains the research to a narrow domain. The first limiting step is the focus on greenhouse gases. This is only one environmental risk that a product system imposes, and a more comprehensive study would include other impacts such as land use, water footprint, ecotoxicity, human health impacts and social impacts. Also, by limiting the present LCA to pavements alone rather than a roadway, we remove the need to account for larger systemic and
societal effects such as induced traffic due to road expansion, increased urban sprawl, and increased reliance on goods transport by vehicle rather than other more efficient means. These broader system-level impacts could potentially trump pavement LCA emissions entirely, since they have to do with the provision of transportation and housing, which are the two of the largest sources of GHG in the entire US economy (EPA 2009).

Additionally, the extrapolation part of this study only considers new concrete construction, without considering reconstruction of existing concrete roads, because data for this was not available through FHWA Highway Statistics or otherwise. While this is estimated to be small, it may skew the validation of the extrapolation procedure to the entire network (above). Another important point is that asphalt and composite pavements are also ignored, which represent 74% and 17% of the entire network by lane-kilometers, respectively. While this was not the present focus, it is important not to lose sight that the vast majority of pavements are asphalt, and many are also composites of asphalt and concrete. The present assumptions were employed with the intent to ignore asphalt, such as the analysis period, which if it were longer would probably involve rehabilitating the concrete with asphalt overlays as is commonly done.

7.3.2 Structure Derivation Procedure

The functional units that are here analyzed incorporate many assumptions in an attempt to derive the “average” structure for each of the functional classes. The need to surmise a single average structure demonstrates very poignantly the simplification that is involved in representing an entire class of pavements through a single structural design—it inherently ignores the variability that may exist across that classification. This variability was accounted for whenever possible, and evaluated through a
sensitivity analysis, but much of the variability was not accounted for. This problem is quite common to most LCA studies, since information on variability and error is often not available for the many pieces of data that are employed in LCA, and if it is available, it is difficult to propagate through to include with the end result.

The first major simplification is relying on the AASHTO design procedure to derive the representative structures. While this is created by and utilized by many state departments of transport, still other DOTs use their own guideline procedures. Also, it is just a guideline and does not necessarily represent actual pavement construction practice. In order to further simplify the AASHTO design procedure of Chapter 4, single values were used for the design inputs. These were selected with the “average” concrete pavement in mind, but may vary significantly from project to project, and are quite influential to the calculation of the structural design. A singular value was selected for all structures for: design life, flexural strength, drainage coefficient, and elastic modulus of concrete. Singular values for each separate structure were used for: load transfer coefficient, serviceability, and modulus of subgrade reaction.

Apart from deriving the design thicknesses, the shoulder and foreslope designs simplify what is actually composing the US pavement network. There is also no accounting for additional parking lanes, turn lanes, median barriers, or other design elements. Other design anomalies that are ignored include tunnels, bridges, and elevated highways. Other construction types are also not evaluated that might not only be significant contributors to benchmark emissions, but might also present design alternatives that have different embodied GHG emissions.

Apart from geometry, material mixes and rehabilitation practices are variable in practice, but simplified here. One concrete mix design, one subbase and base design, and one rehabilitative
treatment is considered. A variety of mix designs are used today, including different aggregate gradings, cement ratios, water-to-cement ratios, and the addition of chemical admixtures. Admixtures include a variety of chemicals that change the material properties of the concrete, including water-reducers, air-entrainers, corrosion-inhibitors, foaming agents, pigments, etc. (ACI 1989).

Many of these design alternatives are interesting areas of future research, especially considering the pavement LCA models that are currently built can easily be adapted to evaluate these alternatives. Such alternatives include roller compacted concrete, full depth concrete reclamation, cement and asphalt treated bases, etc.

### 7.3.3 Life Cycle Assessment Model

There are a few oversimplifications used in the life cycle modeling procedure and data sources that could be improved upon.

For example, AASHTO guidance documents were used to estimate lighting requirements, but these recommendations are likely an overestimate of what is actually practiced, especially for rural applications. An inventory that surveys how much lighting is actually used on pavements in the US would have been a much improved approach.

The influence that pavements have on vehicle fuel consumption is a complex interaction that is not fully understood by the science at present. For this reason, two of the identified effects are outside of the present scope. The first is structural deflection, which may contribute dramatically to the life cycle, especially on asphalt pavements. This effect has yet to be based in a sound theoretical model, in such a way that the magnitude that the influence of the pavement’s material properties on vehicle fuel...
consumption can be isolated from the influence of vehicle parameters and environmental parameters, including tire air pressure, vehicle suspension, tire and air temperature, and a host of other confounding factors. The second ignored effect is the pavement’s effect on air temperature, which can affect the vehicle’s air drag and thereby affect fuel consumption.

One pavement effect on fuel that was included presently is the influence of pavement roughness. In order to estimate roughness of roads as they are exposed to weather and degrade over time, a moderate climate and an extreme climate were modeled in MEPDG, and the midpoint of these two predictions was taken as representative. It is not clear how accurate this is. It does allow for estimation of a mid-range climate, as well as the predicted variability across the different climate types, but there may be better ways to estimate this more accurately. This is important considering its large contribution on the life cycle of many of the functional systems, especially those with high volumes of traffic.

Another complicated effect that is modeled very simply in the present study is that of carbonation. A single carbonation rate was used to estimate baseline emissions, and a single theoretical maximum was used to estimate potential reductions through end-of-life management. This ignores the complexities of this phenomenon, including the influence of climate and moisture on the carbonation rate and depth, as well as the influence that carbonation has on concrete’s compressive strength. This last point is potentially important because of the effect that carbonation has on pavement durability. This is one of many interactive effects within the life cycle that could be explored in future LCA studies.

Modeling traffic delay in the life cycle leveraged the work of another model in order to account for the complexities of traffic dynamics and variable lane closure practices. But the RealCost model has limitations that make its output results only somewhat reliable. For one, when lanes are closed for
construction or repair work, oftentimes detours are set up to divert traffic, which is not included in RealCost. Also, since the model assumes the activity is symmetric on both sides of the road, it is difficult to model closures on two-lane roads. In practice one lane is often closed down at a time, and flagmen at either end of the workzone alternate the traffic flow in both directions through the remaining open lane. This was estimated by specifying in RealCost that “half” of a lane remains open during construction and rehabilitation. Additionally, traffic delay was only assumed to occur during initial construction and subsequent rehabilitation activities, ignoring the inclusion of emergency events as well as construction work of nearby facilities (sidewalks, buildings, and underground sewer and electrical systems) that are common in low traffic urban areas.

7.3.4 Opportunities for Reduction

While the presently analyzed opportunities for GHG reduction provide suggestions for low-hanging fruit, they do not nearly exhaust an entire portfolio of opportunities that may exist.

Reducing cement content through partial substitution with coal fly ash is just one of many potential scenarios. This can also be achieved through a variety of mix designs that require less cement, mix design optimization for maximally reducing cement based on performance requirements, replacement with slag, amongst other strategies. Fly ash was chosen because the trade-offs in the life cycle could easily be accounted for, including increased carbonation depth, and the attribution of emissions to fly ash for its production and transportation. Modeling reduced cement in the concrete mix would involve redesign of the initial pavement structures, as well as potentially affect durability. This makes it more difficult to obtain an equivalent comparison to the life cycle impacts of the baseline
structures. This does, however, present an opportunity for reduction and for future research to quantify other strategies for reducing cement content.

One of the present suggestions is perhaps more theoretical than practical from an economic standpoint: leveraging the carbonation effect through end-of-life management entails crushing reclaimed concrete and exposing it to the open air for extended periods of time, requiring the potentially costly resources of unoccupied space and ample time. The time required to achieve the theoretical limit of 75% carbonation may in fact make this not a cost-effective opportunity for some transport agencies.

Another scenario involves an application of geoengineering: sourcing whiter aggregate for the concrete mix so that the concrete reflects more of the incoming sunlight than it would otherwise. While this presents a significant opportunity to reduce the carbon dioxide equivalence embodied in the pavement life cycle, a couple of important nuances should be made explicit about the limitation of these results. While having some influence on urban heat island effect and reduced lighting requirements, this reduction strategy largely acts by reflecting more of the sun’s radiation out of the earth’s atmosphere. While a relation has been derived to express this effect in terms of GHG-equivalence, it does not have to do with reducing the amount of GHGs emitted during the life cycle, but rather is an instance of geoengineering the earth in order to manage incoming solar radiation. It is also worth noting that the albedo effect is measured relative to the average color of concrete, and so anything lighter in color is attributed negative emissions. This makes sense given the decision to build the road is outside the scope of this analysis, but runs the risk of portraying standard practice in a positive light by attributing it with zero emissions, when more can actually be done to improve the status quo.
In Chapter 6 it is noted that for certain functional classes, near-zero or even negative life cycle GHG emissions are possible. This claim must be made with great care, because it involves a host of assumptions that may not match an actual attempt to reduce carbon. The term “carbon neutral” or even carbon negative, as in this case, is a contentious term because of attacks that have been made on companies claiming carbon neutrality in their operations because they are able to purchase credits that promise reductions in the future rather than now, such as through tree planting (Kleiner 2007). Standards have emerged that specify how to establish carbon neutrality in an accurate manner (BSI 2010). Part of this requirement is to ensure that the future emissions reductions that are promised are in fact acted upon, which in this case means making sure to properly manage the end of life of the pavement, which is to occur at an indeterminable date.

Another area that has been identified as an opportunity for reducing life cycle GHG emissions is to prevent “overdesign.” Concrete pavement thickness, as well as other design elements (dowels, slab length, subgrade preparation, subbase and base thickness and composition, etc.), are chosen to satisfy traffic, climate, and subgrade conditions for a required service lifetime. But long term pavement performance (LTPP) data collection programs have shown that concrete pavements consistently carry more loading than they were designed for (Mack 2010). This tendency to overdesign may be embedded in the AASHTO design procedure, since the method was designed based on empirical observations. The MEPDG design procedure leads to consistently leaner concrete slab designs, in particular for high volume roads. This is reputed to be a more accurate procedure for meeting design specifications, and the resulting leaner structures could make more widespread adoption of the MEPDG procedure a strategy for also reducing life cycle GHG emissions by paving with reduced quantities of concrete. A
structured evaluation of this hypothesis is an area for future work to be done, which can also be
evaluated with an LCA framework as a way to optimize pavement design for reducing carbon emissions.

7.3.5 Cost-effectiveness of Reduction Strategies

In sum, the present and future reduction strategies could be combined with life cycle cost
analysis (LCCA) in order to identify cost-effective or eco-efficient strategies for reducing life cycle GHG
emissions of concrete pavements. LCCA is able to evaluate costs that are incurred by all parties—
contractors that build roads, agencies that maintain them, and vehicle operators that use them—for the
duration of the same analysis period in the present LCA. This combines the insight that LCA can provide
with the practicality of how economically feasible these strategies are. Combining life cycle quantities of
CO$_2$e with dollar amounts can display, for example, that some of the present reduction scenarios can be
achieved at a reduced cost. Partial replacement of cement with fly ash can present one such
opportunity, depending on the relative cost of fly ash to cement. Other reduction scenarios might be
shown to be unfeasible due to high costs per metric ton of CO$_2$e abated. This information would give
transportation agencies easy-to-understand metrics for how to prioritize their efforts to meet current
state and future national GHG regulations, such as California’s “Global Warming Solutions Act” Assembly
Bill 32.
7.4 KEY FINDINGS

The key contribution of this thesis is the quantification of greenhouse gases embodied in the life cycle of new concrete pavements in the US. This includes a benchmark measurement of emissions for current practices, and a measurement of achievable GHG reductions by considering four reduction opportunities. This is done for 6 urban and 6 rural functional systems, both on a per-kilometer basis for the 40 year analysis period, and on a US network-wide basis for each year, presently and extrapolating 50 years into the future. Emissions are quantified in absolute terms (i.e. X metric tons CO$_2$e per km) and in relative terms: so as to 1) compare different functional systems, 2) show the contribution of different components of the life cycle, and 3) show the relative emissions from each year of the analysis period.

The overall key findings are:

7.4.1 Discrete Structures Results

1) The life cycle greenhouse gas emissions per kilometer of new concrete pavement is as follows for the 12 functional systems (all values in metric tons CO$_2$e):

<table>
<thead>
<tr>
<th>Rural Functional System</th>
<th>Metric Tons CO$_2$e</th>
<th>Urban Functional System</th>
<th>Metric Tons CO$_2$e</th>
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<tr>
<td>Interstates</td>
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<td>Interstates</td>
<td>6.2</td>
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<tr>
<td>Other Principal Arterials</td>
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<td>Other Freeways/Expressways</td>
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<td>Minor Collectors</td>
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<td>Collectors</td>
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</tr>
<tr>
<td>Local Roads</td>
<td>0.3</td>
<td>Local Roads</td>
<td>0.5</td>
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</table>

2) **Cement production** has the largest life cycle GHG contribution on all roads: from 51% on urban interstates, to 85% on rural local roads.
3) The majority of emissions occur during pavement construction, constituting about 62% of the total on urban interstates, 75% on rural interstates, and up to 98% on rural local roads.

4) Using a combined strategy of four reduction scenarios, including fly ash substitution, whiter aggregate, carbonation through EOL management, and more frequent concrete rehabilitation, life cycle emissions per kilometer can be reduced by approximately 58% on the largest of roads (urban interstates) and by as much as about 100% on the smallest of roads (rural local roads).

7.4.2 US Network-Wide Results

5) The life cycle greenhouse gas emissions for all new concrete pavements constructed in the US is approximately 2.6 Tg CO₂e per year, or about 0.03% of total emissions in 2009.

6) Applying these reduction strategies to the entire network would result in a reduction of total emissions across the US network by 69%, which is equivalent to closing down 1 coal-fired power plant every 2.3 years.

7.5 CONCLUSION

The conclusions chapter is divided into three parts: validation, discussion, and key findings. Validation is done to compare the present results with other similar studies, both on a project-level and for the national benchmark. Discussion includes the shortcomings of the thesis, and presents potential subsequent opportunities for future research in this domain. Key findings succinctly presents the most significant findings of this thesis.
SECTION V: BIBLIOGRAPHY AND APPENDICES

BIBLIOGRAPHY


**APPENDIX 1**

Assumptions for Structure Designs for AASHTO Design Procedure

<table>
<thead>
<tr>
<th>Functional System</th>
<th>Rural Roads</th>
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<td>Other Prin. Arterial</td>
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<td>Local Road</td>
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*Estimated lane-miles by functional system" from Table HM-60

- **2008**: 122,825
- **2008**: 30,196

*Length by functional system" (miles) from Table HM-20

- **2008**: 4,200,000
- **2008**: 4,200,000

*Vehicle miles of travel, by functional system" (MILLIONS) From Table VM-20

- **2008**: 243,290
- **2008**: 4,200,000

Lanes (Mean)  
- **2008**: 4.1  
- **2008**: 2.0  
- **2008**: 4.0  
- **2008**: 2.0  
- **2008**: 4.0  
- **2008**: 1431

Inner Shoulders  
- **2008**: 2.0

Outer Shoulders  
- **2008**: 2.0

Laned (Mode)  
- **2008**: 2.0

AADT  
- **2008**: 22074

Low End AADT  
- **2008**: 7324

High End AADT  
- **2008**: 35092

AADTT  
- **2008**: 4314

Low End AADTT  
- **2008**: 1431

High End AADTT  
- **2008**: 6857

Single Unit only (%)  
- **2008**: 0.03

Combination only (%)  
- **2008**: 0.17

Direction Distribution  
- **2008**: 0.5

Lane Distribution  
- **2008**: 0.9

Service Life  
- **2008**: 20

Daily Rigid ESALs  
- **2008**: 23,947,182

Low End ESALs  
- **2008**: 7,945,709

High End ESALs  
- **2008**: 38,069,797

Reliability =  
- **2008**: 95%  
- **2008**: 50%

Zr =  
- **2008**: -1.64  
- **2008**: -1.28

So =  
- **2008**: 0.35

Flex Strength S'c =  
- **2008**: 650

Cd =  
- **2008**: 1

J = (dowels w/ J=2.8, No  
- **2008**: 2.8

J (Low End)  
- **2008**: 2.8

J (High End)  
- **2008**: 2.8

Ec =  
- **2008**: 4,200,000

PSIL (72 and 86)  
- **2008**: 4.5

k (granular base) =  
- **2008**: 150

D (inches)  
- **2008**: 11.5

D Low End  
- **2008**: 9.7

D High End  
- **2008**: 12.3

---

4 (Federal Highway Administration 2008)

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## APPENDIX 2

### RealCost Outputs and Subsequent Calculations

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<th>Urban Network</th>
<th>Rural Network</th>
<th>Urban Network</th>
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<td><strong>Work Zone limit (mph)</strong></td>
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## APPENDIX 3

**Key MEPDG roughness values for each functional class in two climate zones (in m/km)**

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<th>Interstates</th>
<th>Other Principal Arterials</th>
<th>Minor Arterials</th>
<th>Major Collectors</th>
<th>Minor Collectors</th>
<th>Local Roads</th>
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<th>Other Freeways and Expways</th>
<th>Other Principal Arterials</th>
<th>Minor Arterials</th>
<th>Collectors</th>
<th>Local Roads</th>
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<td>Other Freeways and Expways</td>
<td>Other Principal Arterials</td>
<td>Minor Arterials</td>
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<th>Local Roads</th>
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<th>Other Freeways and Expways</th>
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## APPENDIX 4

### Life Cycle GHG Emissions Per km for 12 Functional Systems (in metric tons CO$_2$e)

#### RURAL

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<th>Carbonation</th>
<th>Cement Production</th>
<th>Cement Transport</th>
<th>Concrete Mixing</th>
<th>End of Life Transport</th>
<th>Fly Ash</th>
<th>Fuel Consumed from Roughness</th>
<th>Mix Transport</th>
<th>Onsite Equipment</th>
<th>Pavement Demolition</th>
<th>Pavement Rehabilitation</th>
<th>Steel Production</th>
<th>Steel Transport</th>
<th>Traffic Delay</th>
<th>Water Production and Transport</th>
<th>Total</th>
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#### URBAN

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<th>Carbonation</th>
<th>Cement Production</th>
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<th>Concrete Mixing</th>
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<th>Steel Transport</th>
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