Methods, Impacts, and Opportunities in the Concrete Pavement Life Cycle

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EXECUTIVE SUMMARY

Life cycle assessment (LCA) offers a comprehensive approach to evaluate and improve the environmental impacts of pavements. This research explores and advances three key areas relevant to the pavement LCA field: methodology, quantification, and the supporting science. First, a general pavement LCA methodology is put forth that describes the concepts necessary to develop and conduct a comprehensive pavement LCA. Second, the methodology is applied to the concrete pavement life cycle in order to quantify current emissions, identify opportunities for improvements, and calculate the cost effectiveness of emission reduction strategies. Finally, to improve the supporting science for pavement LCAs, a mechanistic model is developed that relates pavement structural and material properties to vehicle fuel consumption.

Development of a standardized pavement LCA framework is essential in order to increase the accuracy and consistency of the LCA approach. This research supports ongoing standardization efforts by proposing good-practice concepts for conducting any pavement LCA. Regardless of an individual project's goal and scope, good practice stipulates that pavement LCAs use a comprehensive life-cycle perspective and provide an adequate level of transparency with regards to the data, functional units, and other important LCA parameters. Adopting a life-cycle perspective ensures that short term gains do not come at the expense of long-term deficits. Drawing boundaries to include all phases of the pavement life cycle—materials, construction, use, maintenance, and end of life—allows for a representative characterization of cumulative environmental impacts over the life of a pavement.

The general methodology is applied to concrete pavements in order to evaluate the impacts of this infrastructure system and demonstrate the application of good-practice pavement LCA. Greenhouse gas (GHG) emissions (characterized using global warming potential) in the concrete pavement life cycle are quantified for twelve functional units, which collectively evaluate average conditions for each major roadway classification in the United States. These results are used to estimate national GHG emissions caused by new concrete pavement construction each year. The functional units also serve as baselines to identify and quantify GHG emission reduction opportunities, both for the mass of reduced emissions and the accompanying cost effectiveness. Among the evaluated reduction strategies, the two that reduce embodied emissions (increased fly ash and reduced overdesign) demonstrate simultaneous cost and emission savings, ranging as high as hundreds of dollars saved per ton of CO_2e reduced. Scenarios also exist where increasing albedo, promoting end-of-life carbonation, and decreasing vehicle fuel consumption through reduced pavement roughness will effectively reduce GHG emissions at costs comparable to the current price of carbon in the global market.

The accuracy and comprehensiveness of any pavement LCA is limited by the ability of the supporting science to quantify the environmental impacts. Pavement-vehicle interaction (PVI) represents a significant knowledge gap that has important implications for many pavement LCA studies. In order to fill this gap, a first-order mechanistic model is developed that rationalizes the impact of deflection within PVI. The model provides a relationship between vehicle mass, material stiffness, structural thickness, and vehicle fuel consumption. The continued development of this model will provide insight into the level of importance of each deflection-related PVI parameter and ultimately help guide pavement design for reduction of vehicle emissions associated with pavement structure and material properties.

KEYWORDS

Life cycle assessment (LCA); life cycle cost analysis (LCCA); pavements; concrete; greenhouse gases (GHGs); global warming potential (GWP); pavement vehicle interaction (PVI)

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1 INTRODUCTION

The construction, operation, and maintenance of the United States roadway system are responsible for substantial energy and resource consumption. The two primary types of pavements are concrete and asphalt pavements, which together make up approximately 4.2 million kilometers (2.6 million miles) of paved public roads in the United States (FHWA 2008). In addition to the need for continually maintaining public roads, this network has been growing each decade, requiring substantial investment for maintenance and new construction. This vast network has major environmental and economic impacts for the nation and the planet.

The cumulative environmental impact of the road network is unknown, though significant greenhouse gases are released during the construction and operation of pavements. Annually, 320 million metric tons (350 million tons) of raw materials go into the construction, rehabilitation, and maintenance of this system (Holtz and Eighmy 2000). The current system of paved roads in the United States handles a volume of traffic on the order of five trillion vehicle-kilometers (three trillion vehicle-miles) per year, or about 13 billion vehicle-kilometers (8.2 billion vehicle-miles) per day (US DOT 2008). Due to high energy demand, road transport contributed the most greenhouse gases (GHGs) of any transport mode in 2007, accounting for 83% of emissions from the transportation sector and 27% of all emissions in the U.S. (EPA 2009).

Due to the high environmental and economic impact of pavements, there is growing interest in the ability to rigorously quantify the performance of pavements. Over the last decade, the construction industry has experienced a dramatic growth in the design of more sustainable buildings, exemplified by the U.S. Green Building Council (USGBC) and its Leadership in Energy and Environmental Design (LEED) rating system (USGBC 2011). The design and operation of pavements in future decades will likely follow a similar path toward greater concern for sustainability, and several "green" rating systems are currently under development for pavements (e.g., Greenroads (2011); FHWA (2011)).

Improving the sustainability of pavements requires a better understanding of how this infrastructure impacts the natural environment. Products and services have impacts throughout their life, beginning with raw materials extraction and product manufacturing, continuing through construction, operation and maintenance, and finally ending with a waste management strategy. Conventional environmental assessments often overlook one or more of these phases, leading to conclusions based on incomplete results. Life cycle assessment (LCA) can be used to evaluate all phases of the life cycle, providing a comprehensive analysis of the environmental burden of this infrastructure system. This research uses LCA to investigate the pavement life cycle, emphasizing the methods and impacts associated with concrete pavements.

1.1 Objectives

The overarching goal of this research is to increase the ability of LCA to evaluate, quantify and help reduce the life-cycle impacts of concrete pavements. This is accomplished through three primary objectives:

1. Develop a comprehensive methodology that puts forth good-practice concepts for conducting a pavement LCA;
2. Use the developed methodology to quantify GHG emissions for concrete pavements, identify strategic opportunities for reducing emissions, and calculate the cost effectiveness of the reduction strategies;
3. Improve the science which supports pavement LCAs by developing a first-order mechanistic pavement-vehicle interaction (PVI) model that relates fuel consumption to pavement material and structural properties.

This document promotes a transparent methodology to evaluate the environmental impacts of pavements. From a methodology perspective, the intent is to promote good practice application of LCA for pavements, thus providing guidance to the pavement community on the development and adoption of standardized pavement LCA protocols. The application of this methodology for a specific concrete pavement LCA study serves two purposes: (1) it demonstrates the approach and execution of the developed methodology, and (2) it provides a quantitative analysis of GHG emissions in the concrete pavement life cycle. Lastly, it is important to acknowledge that the completeness of a pavement LCA is limited by the quality of the supporting science. Building on a previously identified knowledge gap, this research explores the relationship between pavement structure and material properties with fuel consumption by developing a first-order mechanical model that helps describe the PVI phenomenon.

1.2 General Methodology

LCA can be used for any number of purposes. The flexible analysis framework and quantitative approach make LCA useful for establishing environmental footprints, comparing alternative systems, validating and marketing "green" claims, and identifying opportunities for improvement within the life cycle. Arguably the strongest applications are those centered on reducing environmental impact. LCA can be used to generate comprehensive and scientifically-defensible strategies for lowering emissions, reducing waste, and minimizing energy, water, or natural resource consumption. Furthermore, the life-cycle approach ensures that near-term improvements do not come at the expense of long-term deficits. Adopting such robust reduction strategies is the key to establishing an effective path towards reaching environmental goals.

The LCA approach to quantifying environmental burden is formalized by the International Organization for Standardization (ISO) 14040 series. Notable documents in this series are ISO 14040:2006 – Principles and Framework (ISO 2006a) and ISO 14044:2006 – Requirements and Guidelines (ISO 2006b), which together outline many fundamental concepts relevant to developing and conducting an LCA study. ISO breaks the LCA framework into four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. Figure 1.1 depicts these stages and their interrelations. More information regarding the details of each stage can be found in the ISO documents, which are an essential resource for any LCA practitioner.

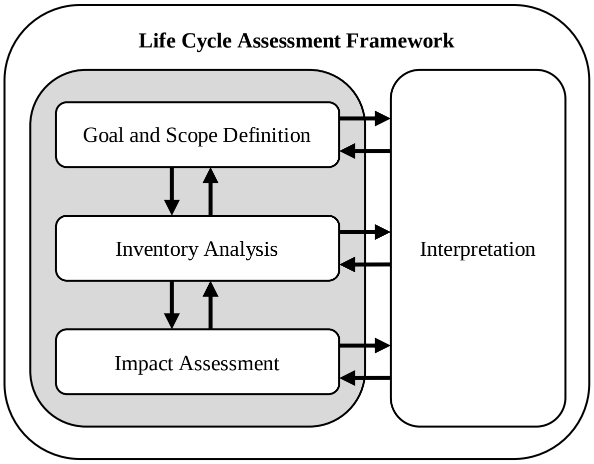

Figure 1.1 – General LCA framework (including four core stages) put forth by the International Organization for Standardization (ISO 2006a)

Data for LCAs come from a wide variety of sources, including government databases, industry reports, system models, and first-hand collection. Since the entire life cycle is being analyzed, the volume of necessary data is often large and overwhelming. LCA software packages, such as *GaBi* (PE International 2011), *SimaPro* (PRé Consultants 2011), and *EIO-LCA* (CMU 2011), not only provide a modeling framework, but also include an abundance of life-cycle data on materials and industrial processes. These types of packages are generally proficient at quantifying upstream impacts for commodities by including large databases, but third-party information is often necessary to combine these data in appropriate ways and to evaluate niche products and processes that are not included in the databases. External models, such as those describing building energy consumption, vehicle dynamics, or electricity generation, are commonly used to complement the core LCA model and provide spatial, temporal, and system-specific data. Such models are particularly useful when characterizing the operation phase of the life cycle.

The ISO guidelines describe a generalized approach for LCA, but do not discuss details relevant to a particular product. Mapping the life cycle, developing functional units, drawing systems boundaries and mining data are left to the discretion and challenge of individual practitioners. The guidelines offer support in the form of suggested accounting practices, allocation procedures, reporting formats, and other protocols, but wisely leave the development of product-specific standardized frameworks in the hands of stakeholders in their respective fields. The pavement community, which includes industry, academics, and public agencies, is tasked with developing an unbiased and comprehensive LCA framework to use in assessments.

1.2.1 Pavement LCAs

Since LCA first started being used to evaluate the environmental impacts of pavements in the late 1990s, there has been general convergence towards accepted practices. However, a recent review of the pavement LCA literature found that there are still notable framework gaps and inconsistencies amongst existing studies, including issues with the functional units, system boundaries, goals, scopes, and data (Santero et al. 2010). Initiatives aimed at identifying framework deficiencies and improving the evaluation process for pavement LCAs are underway, such as the 2010 Pavement LCA Workshop (UCPRC 2010) and the Federal Highway Administration's Sustainable Pavements Program (FHWA 2010). These collaborative efforts will help improve the robustness and uniformity of pavement LCAs, but a universally accepted standardized framework is still under development.

The most crucial methodological decision in a pavement LCA is the selection of system boundaries. From a life-cycle perspective, boundaries should be drawn so that all relevant processes are included in the assessment. When one or more relevant processes are arbitrarily excluded, the quality and confidence of LCA results are jeopardized, as excluded phases and components can have a large impact on the results (Santero and Horvath 2009). Figure 1.2 illustrates a comprehensive map of the pavement life cycle. Because the supporting science is continually uncovering new knowledge relating pavements to environmental impact, it is expected that boundaries will be adjusted as necessary to reflect the current state of the science. The specific boundary used for this research is discussed in Section 2.2.

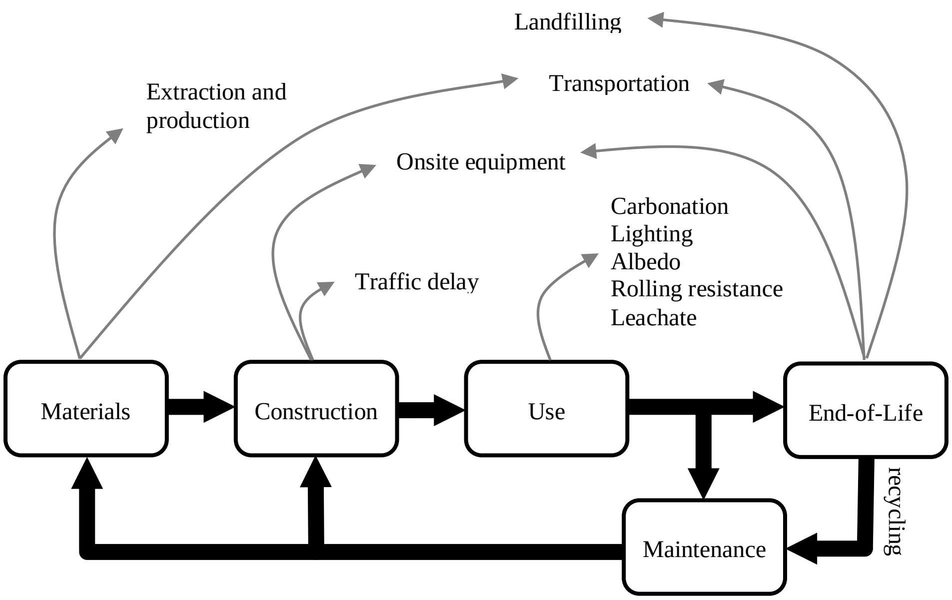

Figure 1.2 – Suggested system boundaries (including life-cycle phases and components) for pavement LCA (Santero et al. 2011)

The goal and scope of the pavement LCA also plays an important role in determining proper system boundaries. Needs differ between pavement LCAs and it is difficult to establish a one-size-fits-all boundary system. For instance, a project-level comparative assessment may draw system boundaries that exclude lighting, carbonation, or other components that are assumed to be equal amongst competing alternatives. Likewise, a policy-level assessment focusing on regional reduction strategies may exclude onsite equipment due to its relatively small impact. The goal and scope also affect other LCA characteristics, such as the functional unit (including the analysis period), environmental outputs, and data sources. For instance, evaluating the water use impact of long-life pavements in California requires a different approach than establishing a carbon benchmark for local pavements across the United States. Whereas policy-level assessments may rely on national averages and other generalities, project-level assessments should be performed using specific design inputs and location-based data. Assessments that compare design alternatives should pay close attention to the functional unit and data sources to ensure that the design equivalent and the data sources are accurately represent the structures being compared.

Movement towards a standardized pavement LCA framework will provide designers, researchers, and other stakeholders to ability to accurately and consistently characterize the impacts of pavement structures. With respect to comparative LCAs, previous studies have lacked comprehensive systems boundaries, leading to inaccurate representations of both the concrete and asphalt life-cycle impacts (Santero et al. 2011). LCA approaches that capture each relevant component of the pavement life cycle will produce more defensible conclusions and provide sounder recommendations. Additionally, LCA practitioners can provide better insight by framing problems statements that respect the variability of pavement design. Given the multitude of design permutations for asphalt, concrete, and composite structures, it is unreasonable for an LCA to definitively determine a best structure for all cases. Rather than draw broad conclusions regarding material choices, practitioners will provide better contributions to the LCA and pavements communities by providing defensible recommendations for clearly described scenarios.

1.2.2 Improving Application of LCA through LCCA

Life cycle cost analysis (LCCA) can evaluate the economic impacts of pavements in various ways. For example, LCCA can be used to compare alternative designs, evaluate payback periods for proposed improvements, or calculate the cost-effectiveness of environmental improvement strategies. Regardless of the approach, accompanying the environmental impacts from LCA with the economic impacts from LCCA creates a marked advancement in the utility of the assessment as a whole. Whereas LCA quantifies the important environmental issues, LCCA provides the necessary economic context to implement those solutions into the marketplace.

The framework for conducting an LCCA for pavements is established by the Federal Highway Administration (FHWA). While the pavement LCA framework is currently standardized only on general levels (i.e., the ISO documents), LCCA has accepted protocols specific to pavement projects. The *Life-Cycle Cost Analysis in Pavement Design* (Walls and Smith 1998), *Life-Cycle Cost Analysis Primer* (FHWA, 2002), and *Economic Analysis Primer* (FHWA 2003) together provide a detailed discussion of the input and outputs of a pavement LCCA. Included are discussions regarding the discount rate, analysis periods, user costs, and other fundamental assumptions. State agencies have largely adopted the FHWA LCCA framework; for example, the California Department of Transportation (Caltrans) has developed protocols based on the FHWA framework, supplementing California-specific data as necessary (Caltrans 2010).

This research uses LCCA to evaluate the cost effectiveness of GHG reduction strategies. This approach allows for the LCA results to be more thoroughly analyzed, including evaluating the practicality of the various reduction schemes. Although the FHWA framework does not specifically address the economics of environmental improvement strategies, the basic principles can be followed to ensure general consistency with established methods. Because the application in this research is essentially a comparison between alternatives (standard designs versus designs with carbon reduction benefits), only the differential costs are considered, which follows the FHWA framework (Walls and Smith 1998).

1.2.3 Transparency

The methodology used to conduct a pavement LCA is itself a valuable contribution, regardless of the numerical results or conclusions. Documenting assumptions, disclosing data sources, and clearly defining goals and scopes serve to establish the framework, or individual methodology, that is used for a particular study. Häkkinen and Mäkelä (1996), Stripple (2001), and Athena (2006) are examples of pavement LCAs that provide reasonably transparent methodologies. While the boundary decisions, functional units, and other study-specific decisions are subject to critique, transparent methodologies allow for the audience to understand the rationale behind the authors' decisions, leading to more robust conclusions and reproducible results.

Table 1.1 describes the basic transparency requirements that should be part of a pavement life cycle analysis. Some requirements are shared between LCA and LCCA, while others are specific to a particular analysis approach. Detailing the process by which each element is determined will help future research build upon the contributed knowledge and framework developments. This research prioritizes transparency by providing descriptions, values, and rationales for each of the elements listed in Table 1.1 as they relate to the project goals and scope. While the results and conclusions provide a snapshot of the role that LCA and LCCA can play in producing more sustainable solutions, the methodology offers a foundation for future research to build upon. In particular, it is recommended that other pavement analyses adopt a similar level of transparency in order to promote best practices in the future.

Table 1.1 – Basic transparency requirements to assist in the understanding and reproducibility of pavement LCAs and LCCAs

Analysis Type	Item	Description
Pavement LCAs and LCCAs	Goal	*The purpose and audience of the study.* The goal helps frame the problem being solved and defines the scope of the study (e.g., functional unit, system boundaries, necessary data sources project- or policy-level scope).
	Functional unit	*The reference that all inputs and outputs are normalized against in order to evaluate the stated goal.* The functional unit ensures that pavements are evaluated and compared against equivalent design and serviceability parameters. Typical functional unit definitions minimally include traffic volume and relevant dimensions (e.g., lane-kilometer, centerline-kilometer).
	Analysis period	*The time period over which the functional unit is evaluated.* The analysis period should be chosen in order to effectively achieve the stated goals. Following LCCA precedent, a rule of thumb is to include at least one rehabilitation activity in the analysis period. Comparative LCAs should ensure that the analysis period adequately captures differing features between compared alternatives (e.g., differing maintenance and rehabilitation (M&R) frequency and intensity).
	Structural designs	*The relevant details regarding the pavement design.* Structural design details provide additional context relative to the functional unit for each design alternative. Layer thicknesses, traffic loading, material properties, location, and other parameters are necessary inputs to the life-cycle inventory (LCI) stage, and can be determined using various pavement design methodologies.
	M&R schedules	*The activities and timing of maintenance and rehabilitation (M&R) activities over the analysis period.* Most pavements will require several M&R activities over the analysis period. M&R schedules can be determined through various sources, such as Department of Transportation (DOT) protocols and standard practices (e.g., Caltrans (2010)). Advanced designs tools, such as MEPDG, can help to define when M&R trigger levels are reached.
Pavement LCAs	LCA system boundaries	*The phases and components considered in the LCA.* System boundaries for pavement LCAs will change based on the goal and scope of the study. Beginning with a comprehensive set of life-cycle phases—materials, construction, use, maintenance, and end of life—and adjusting based on the needs of the study will ensure that system boundaries are systematically, rather than arbitrarily, determined.
	LCI environmental factors (EFs)	*The factors linking processes and materials to environmental outputs.* Each source of environmental output should be connected by an EF to an input defined in the functional unit, structural design, M&R schedule, or other system-defining data. The EF units depend on the input and output that are being linked: for the example of a CO_2 output, materials EFs might be in Mg CO_2/Mg material, or transportation EFs in Mg CO_2/Mg-km traveled. EFs are found in journals, reports, LCI databases, process-specific models, and other sources.
	LCIA methodology	*The method used to transform LCI results into impact categories.* The life-cycle impact assessment (LCIA) stage improves the LCI results by presenting the impact in terms of damage to the natural environment, human health, or natural resources. LCI results are converted to one or more midpoint categories (e.g., climate change) through characterization factors (e.g., global warming potential), which normalize similar pollutants to a single metric (e.g., CO_2, CH_4, N_2O, and other GHGs to CO_2e). Various models, databases, and reports are available to assist in the characterization process, including TRACI (EPA 2011), IPCC (2007), and CML (2011).
Pavement LCCAs	LCCA system boundaries	*The types of costs considered in the LCCA.* Pavement LCCAs can include agency and/or user costs within the system boundaries. Agency costs are the costs incurred by the DOT (or other owner) for the construction, M&R and end-of-life activities. User costs are the costs incurred by the public (e.g., drivers, residents) and are typically limited to costs related to traffic delay due to construction activities, although accident costs are sometimes included as well. A wider system boundary may include user costs related to noise or property values. More information on LCCA costs can be found in FHWA (2003) and Curry and Anderson (1972).
	Discount rate	*The value (or range) used to model the time value of money.* The discount rate is used in LCCAs to convert future costs to present costs. The FHWA recommends using the White House Office of Management and Budget (OMB) Circular 94 to estimate the discount rate, which currently recommends a 2.3% rate (OMB 2010). However, state DOTs typically use a range of 3–5% in LCCAs (Rangaraju et al. 2008). Given the uncertainty and variability of the discount rate, it is recommended that a sensitivity analysis be conducted for a range of discount rate values.
	Costs	*The material, activity, and user unit costs.* The LCCA should include the unit costs for each of the materials, activity, and/or user costs in the system boundary. Unit costs are available through a variety of sources, depending on the type of cost being evaluated. Common sources include general materials inventories (e.g., USGS (2011)), DOT databases (e.g., Caltrans (2011)), or relevant industry organizations.

1.3 Overview of Existing Research

A review of the existing pavement LCA research is useful in establishing the current state of the practice. Between the published record and publically-available tools, a foundation has been laid for conducting a pavement LCA. Identifying the strengths and weaknesses of the existing research ensures that this and future studies continue to build upon the work that others have done in this field.

1.3.1 Pavement LCA Literature

The pavement LCA literature is comprised of technical reports and journal papers that apply LCA to various pavement design and case studies, often with the goal of comparing alternatives for a given scenario. These studies are commissioned and produced by various stakeholders in the pavement community, including government agencies, industry organizations, and academic institutions. Aside from providing discrete solutions to explicitly defined problems, the methods and outputs considered in each study—including the goals, scopes, and results—offer insight into the types of issues being addressed, the comprehensiveness of the analyses, and the knowledge gaps that need to be filled in order to provide more robust conclusions.

A 2010 report conducted by the Lawrence Berkeley National Laboratory (LBNL) reviewed the literature to evaluate the overall utility of existing research and provide recommendations for filling identified gaps (Santero et al. 2010). The report finds that most studies are project-specific and that the conclusions are not necessarily generalizable to scenarios outside of the defined scope. Moreover, system boundaries are not comprehensively drawn to include potentially influential elements of the life cycle, such as the use phase. The conclusions across different studies are often in disagreement, most notably when comparing different pavement materials (i.e., asphalt versus concrete); for instance, while most pavement LCAs quantify energy consumption, studies often contradict one another regarding whether asphalt or concrete is more energy-intensive over the life cycle. In summary, LBNL concludes that the existing literature provides useful data and establishes an approach to quantifying certain aspects of the pavement life cycle, but its utility in decision-making processes is limited by the aforementioned and other shortcomings.

Viewed from a holistic perspective, the existing literature highlights important concepts that need to be addressed in order to improve the application of LCA to pavements. Foremost, the development of a standardized framework will reduce inconsistencies across study methodologies. Amongst other improvements, standardization will ensure that system boundaries are comprehensively drawn for a given goal and scope. The continual advancement of the supporting science is a critical element as well, since pavement LCAs are only as accurate as the underlying data and relationships. Filling knowledge gaps (e.g., mechanistic pavement-vehicle interaction models, improved carbonation data, better understanding of project-level albedo impacts) will improve the accuracy of pavement LCAs and allow the assessment process to provide robust solutions to a wider set of problems.

1.3.2 Pavement LCA Tools

Pavement LCA tools expedite and simplify the assessment process. Built-in databases and established process relationships allow LCAs to be performed quickly and require less knowledge than creating an assessment from the ground up. As defined for this research, tools are considered a particular form of a model that is designed for and distributed to a larger audience. A number of pavement LCA models are discussed in the literature (e.g., Stripple (2001); Huang et al. (2009)), but often refer to internal models used for specific projects. This overview focuses on publically-available tools, evaluating their scope in order to quantify the current state of the practice.

Table 1.2 lists six pavement LCA tools available to the public. These represent the current state of the practice with regards to LCA tools available to pavement engineers and other practitioners. Rather than attempt to be an exhaustive set of all tools measuring the environmental impact of pavements, this list includes only those LCA-based tools that could be effectively evaluated through their use and/or supporting documentation. There are a number of LCA tools and models that include pavements within their general scope (e.g., BEES, SimaPro), but are not specific to pavements and do not define themselves as pavement LCA tools.

Table 1.2 – Publically-available pavement LCA tools reviewed in this research

Tool	Developer	Interface	Pavement types	Reference
asPECT	Transport Research Laboratory	GUI	asphalt only	TRL (2011)
BenReMod	University of Toledo	web-based	all types	Apul (2007)
CHANGER	International Roadway Federation	GUI	all types	IRF (2011)
GreenDOT	AASHTO	spreadsheet	all types	AASHTO (2010)
PaLATE	University of California, Berkeley	spreadsheet	all types	Horvath (2004a)
PE-2*	Michigan Technical University	web-based	all types	MTU (2011)

*beta version, not yet released

The bulk of pavement LCA tools are focused on embodied emissions, transportation, and construction processes. Table 1.3 shows the phases and components that are included within the system boundary of each tool. It should be noted that without a standardized pavement LCA framework (as discussed in Section 1.2.1), definitions of phases and components will vary between tools. Table 1.3 evaluates the tools with respect to the system boundaries set in this research. The use phase and traffic delay are generally excluded from the boundaries of existing tools. The notable exception is *PE-2*, which calculates emissions from traffic delay caused by construction and maintenance activities. The addition of traffic delay impacts is important in that it begins to expand the boundaries beyond the typical, materials-centric perspective. *GreenDOT* also includes the use phase components of lighting and vehicle operation emissions, but does not differentiate impacts based on pavement properties.

The general omission of the use phase and the traffic delay component of the construction and maintenance phases indicates the difficulty of generalizing these elements of the pavement life cycle. Whereas individual LCA studies benefit from well-defined goals and functional units, LCA tools are designed to be applied to any number of different scenarios. Embodied emissions, transportation, and construction processes can be universally determined through established methods set by previous LCA studies. Moreover, these activities can be modeled using basic mathematics, thus eliminating the need for external models or development of novel mechanistic relationships. Conversely, impacts from the use phase components are largely based on maturing scientific fields, resulting in limited data availability and an incomplete understanding of the underlying physical phenomena. Traffic delay impacts can be quantified using existing models, but implementation into an LCA tool involves more complicated algorithms than for the embodied emissions, transportation, and construction processes.

Table 1.3 – Life-cycle phases and components of reviewed pavement LCA tools

	Materials		Construction		Use				Maintenance				End-of-Life				
Tool	Extraction and production	Transportation	Onsite equipment	Traffic delay	Carbonation	Lighting	Albedo	PVI	Extraction and production	Transportation	Onsite equipment	Traffic delay	Onsite equipment	Transportation	Landfilling	Recycling processes	Carbonation
asPECT	•	•	•						•	•	•		•	•	•	•	
BenReMod	•	•															
CHANGER	•	•	•						•	•	•		•	•			
GreenDOT	•	•	•						•	•	•		•	•			
PaLATE	•	•	•						•	•	•		•	•	•	•	
PE-2	•	•	•	•					•	•	•	•	•	•	•		

The set of publically-available pavement LCA tools offer pavement engineers and other practitioners a streamlined approach to evaluating the environmental impact of certain life-cycle phases. Assuming that the data and imbedded process relationships are accurate, the embodied emissions, transportation, and construction processes can be effectively modeled using one or more of these tools. Future research could validate the tools against one another, comparing inputs and outputs in order to determine their agreement. With respect to conducting a comprehensive LCA, tools can expedite the assessment process for more established phases and components while requiring LCA experts to integrate the more complex and uncertain processes, such as albedo and PVI. As the science continues to mature and mechanistic relationships are improved, tools can begin to implement these findings into their scopes in order to develop a more comprehensive portrayal of the environmental impact of pavements.

2 GREENHOUSE GAS IMPACTS AND OPPORTUNITIES FOR CONCRETE PAVEMENTS

This section uses life cycle assessment to quantify greenhouse gas emissions in the concrete pavement life cycle. GHG emissions, characterized by their global warming potential, are quantified for a number of purposes, including quantifying emissions for current practices, estimating national emissions for all new concrete pavements, and evaluating potential GHG emission reduction strategies.

2.1 Goal

The current research evaluates the life-cycle GHG emissions associated with new and reconstructed concrete pavements. GHG emissions are characterized using global warming potential (GWP) characterization factors. Each relevant phase and component of the pavement life cycle is investigated and quantified in order to quantify current emissions and identify opportunities for emission reductions. The initial quantification establishes the current state of the practice, while improvement strategies offer a path towards reducing the impacts of current and future pavement structures. To effectively characterize a wide breadth of pavements, twelve related, but independent, road designs are analyzed. These designs represent each FHWA roadway classification, ranging from rural local roads to urban interstates. This allows for an evaluation of multiple roadway functions and offers the capacity to estimate impacts across the entire U.S. pavement network. The specific objectives of the project are as follows:

1. Develop and apply a comprehensive pavement LCA methodology for concrete pavements.
2. Quantify life-cycle GHG emissions in order to capture (a) each FHWA roadway classification, and (b) all relevant life-cycle phases.
3. Quantify life-cycle GHG emissions of all concrete pavements that are constructed each year in the U.S.
4. Identify and quantify strategies for GHG reductions for each roadway classification; estimate the cost-effectiveness of the reduction strategies using LCCA principles.

These objectives will provide insight into where GHG emissions are occurring in the concrete pavement life cycle, as well as help to develop strategies that will reduce those emissions. Moreover, the LCA model and approach utilized in this research will serve as a foundation for future work, such as expansion of reduction strategies, analysis of new pavement technologies, and evaluation of proposed environmental policies.

This research is intended for a broad audience. The general concepts and conclusions can help decision-makers in industry organizations and governmental agencies adopt more sustainable pavement design practices. LCA practitioners, pavement engineers, and other technical experts can use the methods, data, and results to quantitatively evaluate GHG emission footprints and reduction strategies for specific pavement applications.

2.2 Scope

This study analyzes the GHG emissions of new and reconstructed concrete pavements. In general, the scope is drawn to include processes that are relevant to the pavement itself, thus excluding larger issues related to roadway transportation. The decision to build a roadway where one did not previously exist involves a dynamic and complex set of economic and environmental impacts related to increased mobility and accessibility. While these are important issues, focusing on pavement-specific impacts allows for a more refined and specific study, which ultimately may be used in broader assessments that address the transportation sector as a whole. The following subsections describe the functional unit, the system boundary, and the impact assessment method used to meet the objectives presented in Section 2.1.

2.2.1 Functional Units and Pavement Structures

The functional unit is a reference unit that allows for consistent comparisons between different products and comparison of results across different studies. This research adopts multiple functional units in order to characterize the various classifications of concrete pavement roadways in the United States. Representative structures for each FHWA roadway classification are developed and analyzed over one centerline-kilometer (centerline-mile)[*] for the respective traffic loadings presented in Tables 2.1 and 2.2. Centerline lengths are used so that each of the twelve classifications (six rural and six urban) can be evaluated based on their cross-sectional geometric and material design. The number of lanes, average passenger and truck traffic, and lane widths for rigid pavements are taken from *Highway Statistics 2008* (FHWA 2008). Based on this data, structures are derived using American Association of State Highway Officials (AASHTO) pavement design methods (AASHTO 1993; AASHTO 2004). Summaries of the analyzed roadways are found in Tables 2.1 and 2.2, assumed parameters based on FHWA and AASHTO design methods are found in Table A.1, and corresponding material masses are found in Tables A.10 and A.11. A step-by-step breakdown of the FHWA data and derivation of the AASHTO '93 design procedure is found in Loijos (2011). While still commonly used, it should also be noted that the AASHTO '93 design procedure is considered outdated, since the more robust, climate-specific MEPDG and related mechanistic-empirical methods now exist (Portland Cement Association 2009). The potential GHG emission reductions that are possible due to switching from AASHTO '93 to MEPDG are evaluated in Section 2.6.1.6.

The concrete mix uses 335 kg/m^3 (567 lb/yd^3) of cementitious material (90% portland cement, 10% coal fly ash), a water-to-cement ratio of 0.45, and crushed aggregate for the remaining material, with a density of 2,350 kg/m^3 (147 lb/ft^3) (ACPA 2011). The fly ash substitution value is based on an estimated national average utilization of fly ash and cement in concrete in 2008 (ACAA 2009; USGS 2010). It is important to note that the 10% fly ash is not necessarily a typical replacement rate for concrete mixes due to potentially poor resistance to alkali silica reaction (ASR). While the average value is used here to meet the stated objectives (i.e., represent gross national averages), a project-specific concrete LCA should acknowledge that a minimum 15% replacement rate is probably more realistic and corresponds to many state DOTs thresholds (ACPA 2011). Moreover, supplementary cementitious materials (SCMs) other

[*] Results are given in both International System of Units (SI) and U.S customary units. The functional unit length is necessarily

than fly ash are also commonly used in concrete mixes. Future research could include a range of mix designs in order to test the sensitivity of the results to variable levels of other SCMs.

Table 2.1 – Analyzed pavement designs: rural roadways (SI units, see Table A.8 for U.S. units)

	Interstate	Principal arterial	Minor arterial	Major collector	Minor collector	Local
Function definition						
AADT (vehicles/day)[1]	22,074	6,414	3,084	1,219	574	177
AADTT (trucks/day[2]	4,415	706	308	85	40	12
Total lanes	4[3]	2	2	2	2	2
Lane width (m)	3.7	3.7	3.7	3.4	3.4	2.7
Corresponding AASHTO design						
Shoulder width (m)	1.2 / 3.0[4]	2.4	2.4	1.8	1.5	0.6
Concrete thickness (mm)	292	203	191	152	127[7]	102[7]
Base thickness (mm)	152	152	152	152	0	0
Steel dowel diameter (mm)[8]	38	32	-	-	-	-

Table 2.2 – Analyzed pavement designs: urban roadways (SI units, see Table A.9 for U.S. units)

	Interstate	Freeway	Principal arterial	Minor arterial	Collector	Local
Function definition						
AADT (vehicles/day)[1]	78,789	53,809	19,631	9,729	4,221	980
AADTT (trucks/day)[2]	6,303	2,152	785	389	169	39
Total lanes	6[3]	4[3]	4	2	2	2
Lane width (m)	3.7	3.7	3.7	3.7	3.4	2.7
Corresponding AASHTO design						
Shoulder width (m)	3.0	1.2 / 3.0[4]	2.4[5]	2.4[5]	2.4[5,6]	2.1[5,6]
Concrete thickness (mm)	305	279	216	178	165	127[7]
Base thickness (mm)	152	152	152	152	0	0
Steel dowel diameter (mm)[8]	38	38	32	32	-	-

[1] AADT: annual average daily traffic (two way)
[2] AADTT: annual average daily truck traffic (two way)
[3] Two carriageways with separating median
[4] Inner / outer shoulder width. Includes aggregate in concrete, base, and foreslope elements. Minimum foreslope of 4H:1V is used.
[5] Urban curb and gutter design with no foreslope
[6] Shoulders are parking lanes
[7] These pavements are thinner than some states allow. However, the AASHTO '93 design procedure was still followed to remain consistent.
[8] Dowel length is 0.46 m, lateral spacing is 0.23 m, steel density is 7,850 kg/m^3, and concrete slab length is 4.6 m.

The analysis period begins at initial construction and continues 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 (EOL). Concrete rehabilitation includes 4% slab replacement and complete surface grinding. 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 surveys conducted by FHWA and Mississippi DOT of other state DOT LCCA procedures, which reflect agencies' experience on how long pavements can predictably last (Rangaraju et al. 2008; MDOT

2007). While a 40-year analysis period is appropriate for this study, the results and conclusions for comparative LCAs (such as those comparing asphalt and concrete alternatives) may be more sensitive to the analysis period. For such studies, it is important the analysis period appropriately captures any differences in expected service life, as well as differences in maintenance frequency and intensity.

As previously stated, these functional units are meant to represent average concrete structures for each of the FHWA roadway classifications. In reality, concrete pavement designs will vary significantly from one pavement to the next, even if the basic structural inputs are the same. Regional climate, local design practices, budget, service life, material availability, and other factors play a role in the design process. There is also significant variation within each roadway classification, making it difficult to adopt a single representative structure. For instance, urban interstates routinely support between 30,000 and 130,000 vehicles per day (FHWA 2008), but the weighted average (79,000) is used in this analysis. Such a method is appropriate given the project goals stated in Section 2.1, but may also fail to adequately capture the impacts caused by atypical structures within each classification. Project-specific analyses are better suited to accurately quantify the impacts associated with a particular, well-defined pavement.

2.2.2 System Boundary

Figure 2.1 presents a simplified flow chart that illustrates the phases and components included within the system boundaries for this study. Each phase of the life cycle is represented: materials, construction, use, maintenance, and end of life. The phases are broken down into multiple components, each of which describes a more precise interaction between concrete pavements and the environment.

As with any LCA, the system boundaries will necessarily truncate some processes and exclude other processes altogether. Such truncations and exclusions are done under the assumption that their influence on the results is insignificant (generally less than one percent of overall life-cycle emissions). For example, these exclusions include 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. Upstream emissions associated with fuel and electricity production for cement manufacturing are not included, because of their omission in the antecedent study (Marceau et al. 2006). However, these upstream emissions are included in other processes in the life cycle. Given the goal of this assessment to establish general quantifications and identify opportunities for emission reductions, the loss of accuracy associated with excluding these elements is considered acceptable.

Distinguishing a roadway LCA from a pavement LCA necessitates allocating certain components based on their differential impact, relative to some baseline. For example, vehicle fuel consumption is only allocated to a pavement based on roughness increases over the life cycle. Thus, the pavement roughness at initial construction is taken to be the baseline roughness, and GHG emissions from fuel consumption are calculated based on the progressive deviation from that initial roughness. Deflection-based fuel consumption is excluded from this section due to the assumption that deflections do not change over the life cycle, as well as limitations with the accuracy of existing methods (see Section 3 for a more involved discussion, including limitations of the proposed deflection model). This differential approach ensures that impacts are only allocated to the pavement that are caused (or can be controlled) by the pavement itself. Similar differential approaches are applied to pavement albedo and lighting, which are assumed to be zero over the life cycle, but are quantified as improvement opportunities in Section 2.6. Of note is that comparative assessments may need to establish different baselines in order to capture fuel consumption, albedo, and lighting differences between pavement types. Depending on the goal scope, the baselines established for this study may not be applicable to subsequent studies.

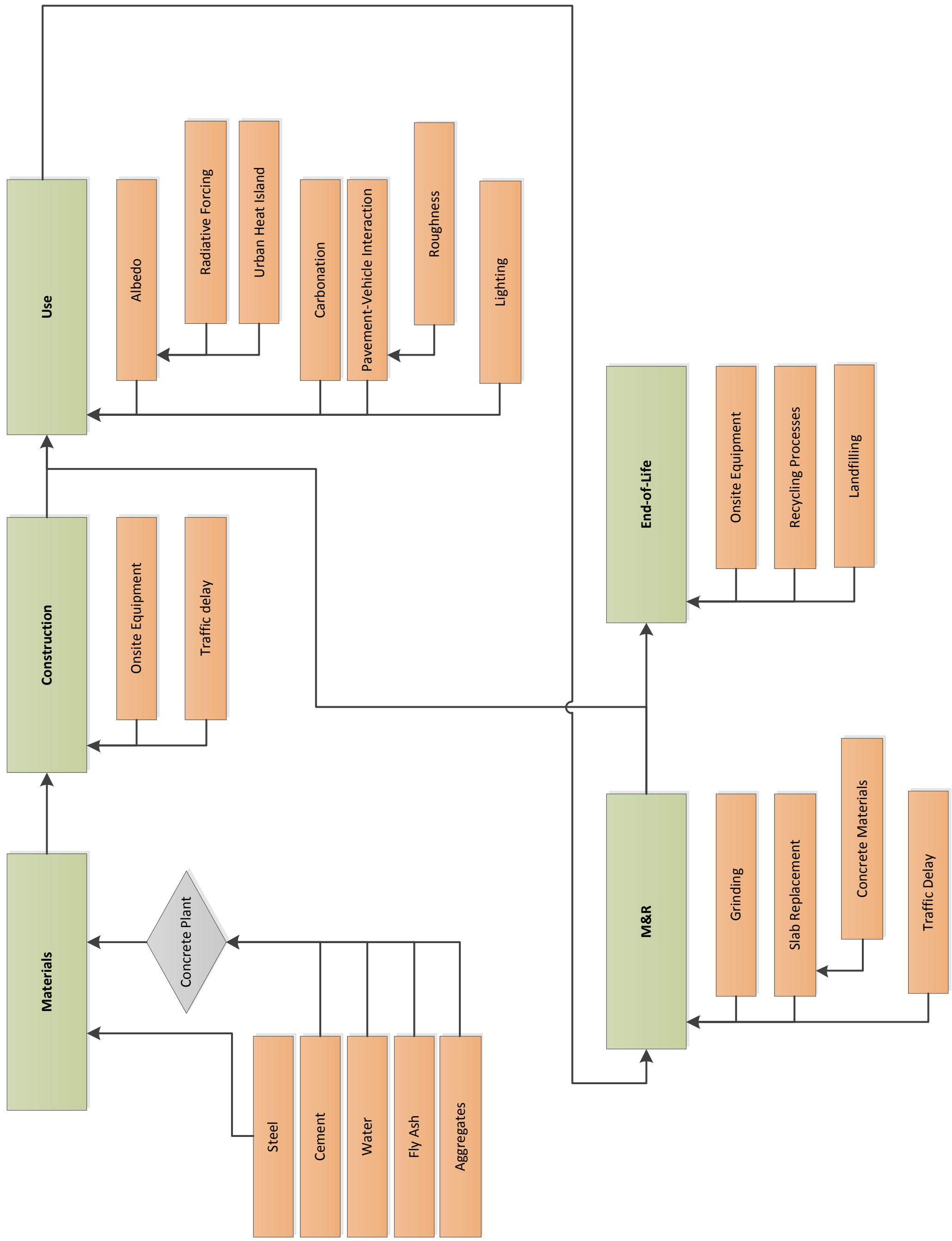

Figure 2.1 – Flowchart representing a simplified version of the MIT pavement LCA model (note: figure excludes transportation and upstream emissions, which are considered in the system boundary)

2.2.3 Impact Assessment Method

GHG emissions are normalized using their global warming potential, as measured in carbon dioxide equivalents (CO_2e). GWP is a common characterization method to evaluate the impacts of GHG emissions on climate change. This research uses the Centre for Environmental Studies of the University of Leiden's "CML" method for GWP characterization (CML 2011), which cites the 2007 "Fourth Assessment Report" by the Intergovernmental Panel on Climate Change, and has been updated to reflect the latest IPCC data (PE International 2011). This assumes a 100-year time horizon for greenhouse gas perpetuity, which is a convention amongst regulations, such as the Kyoto Protocol (IPCC 2007). The procedure for characterization and normalization of GWP 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 than carbon dioxide over the 100-year time horizon. While climate change is a preeminent environmental issue, it is important to acknowledge that other impact categories (e.g., human health impact, water consumption, energy consumption) need to be considered within a comprehensive sustainability framework for pavements.

2.3 LCA Modeling

This section presents the LCA modeling approach used to evaluate the GHG emissions of concrete pavements. The modeling framework, data sources, calculations, and assumptions are summarized and presented. To accurately represent all materials and processes within the system boundary over the 40-year analysis period, each of the five pavement life-cycle phases are considered: materials, construction, use, maintenance, and end of life recycling and disposal.

2.3.1 Building the MIT LCA Model

The LCA software *GaBi* (version 4) by PE International is used as the analysis platform (PE International 2011). *GaBi* allows for creating life-cycle models, generating life-cycle inventories for the model, comparing different scenarios, and conducting basic statistical analysis. The platform allows for data to be extracted from the existing database, as well as for outside data to be incorporated to create unique industrial processes from scratch. Through this customization process, the pavement life cycle can be comprehensively evaluated based on the best information available in the literature, external models, and other sources.

One of the primary benefits of *GaBi* for the present purpose is that the modeling of industrial processes and environmental flows into and out of these processes can be parameterized, so that variables representing 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 pavement albedo is defined as parameter "albedo" in the *GaBi* model, with a nominal value of 0.325, and a range of variation can be specified for the variable as well, which for concrete pavement albedo generally ranges from 0.25–0.40 (ACPA 2002). Parameterization enables an understanding of how the resulting life-cycle impacts change under a variety of different scenarios, such as a range of different pavement designs.

Additionally, parameterization within *GaBi* allows for estimation of variability and includes a sensitivity analysis tool that enables understanding of the sensitivity of the results to variation of the input parameters. Since this variation is expressed as a percentage in *GaBi*, a limitation is that this assumes all parameters vary equally in the positive direction as in the negative direction, as well as being uniformly distributed. In actuality, the distribution of values for a given parameter may not be symmetric. Despite this limitation, a coarse sensitivity analysis still offers value and is provided in Section 2.5.

2.3.2 Inventory Data

The life-cycle inventory data for the analysis is taken from various sources, including the published literature and LCI databases. Creating an LCA model for a large, complex system, such as an interstate highway, requires thousands of individual data points, and the current study uses the best available data. Tables 2.3 through 2.5 summarize the key values used in this research. As with all LCI data, values and sources differ between studies, and the selection of the present data sources are the most up-to-date, peer-reviewed, comprehensive in scope, temporally representative of 2008, and geographically representative of the U.S. However, it is important to note that there is inherent uncertainty and variability in these numbers. In particular, GHG emissions from cement production tend to vary significantly based on the type of kiln and energy source. The cement CO_2e factor used here represents average U.S. emissions based on a 2006 PCA study (Marceau et al. 2006). It is expected that this will decrease over time as wet kilns are phased out and other efficiency improvements are implemented. Section 2.5 performs sensitivity analyses to account for the uncertainty and variability of cement and other factors in the LCA. The sensitivity tests the influence of the various input parameters within a reasonable range of possible alternative values.

Table 2.3 summarizes the GWP emission factors for pavement materials and onsite equipment used in construction. Table 2.4 summarizes the transportation emission factors and distances for paving materials. Table 2.5 summarizes the key parameters for components of the maintenance and use phase of the life cycle. Although efforts have been made to obtain accurate and representative data, the broad scope of this assessment necessitates the use of generalized and average numbers. Project-specific analyses will often have access to information that can be used to better characterize the inputs, such local transportation distances, production processes, and specific mix designs. Other pavement LCAs will likely have different data requirements and should therefore evaluate specific data needs independently. A detailed description and derivation of the data used in this research is found in Loijos (2011).

Table 2.3 – Inventory data for significant materials and construction processes

Material	GWP emissions factor[1]	Source
Aggregate/Recycled concrete crushing	0.0032 kg CO_2e/kg aggregate	Zapata and Gambatese (2005)[2]
Concrete mixing	0.0004 kg CO_2e/ kg concrete	Zapata and Gambatese (2005)[2]
Cement	0.928 kg CO_2e/kg cement	Marceau et al. (2006)
Fly ash	0.01 kg CO_2e/kg fly ash	PE International (2011)
Steel dowels	1.24 kg CO_2e/kg steel	Worldsteel (2011)[2]
Onsite equipment	0.0025 kg CO_2e/kg concrete placed/removed	Zapata and Gambatese (2005)[2]
Water	0.005 kg CO_2e/kg water	PE International (2011)
Landfill of concrete[3]	0.02 kg CO_2e/kg waste concrete	PE International (2011)
Diesel fuel (input)	0.46 kg CO_2e/L (2.8 lbs CO_2e/gal) well-to-tank 3.17 kg CO_2e/L (26.5 lbs CO_2e/gal) well-to-wheels	PE International (2011)
Gasoline (input)	2.56 kg CO_2e/L (21.4 lbs CO_2e/gal) well-to-wheels	PE International (2011)
Electricity (input)	0.79 kg CO_2e/kWh	PE International (2011)

[1] U.S. units for masses are proportional, i.e. 1 kg CO_2e/kg material equals 1 pound CO_2e/pound material
[2] CO_2e emission factor value was derived from data reported in the given source
[3] 50% concrete is landfilled at end of life, 37% is closed-loop recycled as aggregate, and 13% is open-loop recycled for unrelated purposes such as general fill (no burden or credit is assigned for open-loop recycling) (Kelly 1998).

Table 2.4 – Transportation distances and modes for all materials at each step in life cycle

Material	Truck distance [% by mode]	Rail distance [% by mode]	Barge distance [% by mode]
Emission factor[1]	*89 (0.29)*	*31 (0.10)*	*34 (0.11)*
Aggregate[2]	50 km (31 mi) [61%]	510 km (315 mi) [27%]	170 km (110 mi) [12%]
Cement[3]	170 km (104 mi) [94%]	1000 km (620 mi) [3%]	5000 km (3100 mi) [0.5%]
EOL concrete, recycled and virgin aggregate[2]	50 km (31 mi) [100%]	-	-
Steel dowels[2]	590 km (366 mi) [100%]	-	-
Ready mix concrete[2]	40 km (25 mi) [100%]	-	-

[1]PE International data. SI units in g CO_2e/Mg-km and U.S. units in pounds CO_2e/t-mile in parentheses
[2]Adapted from BTS (2007). Aggregate transport used as proxy for demolished concrete transport.
[3] Percentage by mode and import distance estimated from USGS (2009). Average truck transport from Miller and Osborne (2010).

Table 2.5 – Summary of key input parameters for the maintenance and use phases

Life-cycle component	Key factors	Key sources
Rehabilitation	4% full depth repair and diamond grinding at years 20 and 30. 1,576 L diesel/ln-km per diamond grinding activity (670 gal /ln-mi)	Rangaraju et al. (2008) MDOT (2007) IGGA (2009)
Albedo	Baseline albedo α = 0.33. Radiative forcing: 2.55 kg CO_2e/0.01 decrease in albedo/m^2 (0.53 pound CO_2e/0.01 decrease. in albedo/ft^2) Urban Heat Island: 4.85 x 10^{-3} kg CO_2e/0.01 decrease in albedo/m^2 (1.0 x 10^{-3} kg CO_2e/0.01 decrease in albedo/ft^2)	Akbari (1999) Rosenfeld et al. (1998)
Carbonation	Carbonation rate (k)[1]: 1.58 mm/y$^{(1/2)}$ (0.06 inch/y$^{(1/2)}$) Depth of carbonation: $d = k\sqrt{t}$ Carbonation reinitiates at each rehabilitation	Lagerblad (2006)
Pavement roughness	Cars: 4.2% increase in gasoline fuel / increase in IRI by 4 m/km (250 in/mi). Trucks: 2.8% increase in diesel fuel / increase in IRI by 4 m/km (250 in/mi)	Zaabar and Chatti (2010)
Traffic delay	*RealCost* used to estimate the traffic delay 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 *RealCost* inputs can be found in Table A.2	*RealCost* model (FHWA 2010) Caltrans (2010)
Pavement lighting[2]	ε = 100,000 lumens/kW MI_{avg} = 9; 8; 9; 8; 6; 5 lumens/m^2 t = 160,600 hours	AASHTO (2005)

[1] Carbonation rate varies widely in the literature (see Gajda (2001), Galan et al. (2010), Lagerblad (2006), and Khunthongkeaw et al. (2005), for example), and depends on material properties and exposure conditions. 1.5 mm/y$^{(1/2)}$ represents a reasonable midpoint found in several sources, which increases by 5% with 10% fly ash in the mix (Lagerblad 2006).

[2] These values represent the baseline lighting assumptions, but no GWP is attributed to the life cycle in the base case, as the GWP is attributed to the decision to build a roadway, regardless of pavement design. Increasing pavement albedo, however, can reduce the lighting demand due to increased reflectivity, so these differential changes from the base case are accounted for in the albedo strategy in Section 2.6. Average maintained illuminance (MI_{avg}) is the following order: interstates; other fwy/expy; other principal arterial; minor arterial; collector; local road.

2.4 GHG Emission LCA Results

This section presents the results from the modeling methodology outlined in Section 2.3. The results include an estimation of the life-cycle GWP for each of the twelve roadway classifications, broken down by the impact associated with each life-cycle component. 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 period. A sensitivity analysis is used to evaluate the variation in these results due to traffic volume (and the associated structural requirements), traffic delay, as well as numerous other pavement life-cycle parameters. Lastly, each representative structure is extrapolated across all lane-kilometers (lane-miles) in its respective roadway classification 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.

2.4.1 Impacts for the roadway classifications

The life-cycle GHG emissions, expressed in GWP, for twelve different classifications of new concrete pavements are presented in Figures 2.2 and 2.3. Figure 2.2 presents the results in absolute terms, while Figure 2.3 presents the results by the percent contribution from each phase. These quantify the GWP for new concrete construction, not reconstruction, although the data and results can be extended to reconstruction with only minor modifications. The results establish a baseline for seeking reduction opportunities, and the scope of analysis has been appropriately tailored to this. As such, the approach and results are not sufficient for comparative purposes, such as comparing to alternative materials like asphalt pavements. Additionally, the system boundary and allocation procedure have been chosen so as to capture impacts of the decision to build a pavement, not the decision to build a roadway. As distinct from a roadway LCA, conducting a pavement LCA necessitates attributing GWP from certain components based on their differential impact, as has been done with the following use phase components: pavement albedo, lighting, traffic delay, and fuel consumed due to roughness. Since the contribution from the carbonation component is negative, the totals for all pavements in Figure 2.3 are the vertical extent *minus* the carbonation. These results are representative for typical scenarios within each roadway classification, although the results for a given project may differ from those of the broader class. This variability has largely been captured and is presented in Section 2.5.

Total life-cycle GWP range from 340 Mg CO_2e/km (600 t CO_2e/mi) on the rural local road to 6,300 Mg CO_2e/km (11,000 t CO_2e/mi) on the urban interstate. The wide difference is largely due to the fact that interstates are much more massive structures, both in terms of the thickness of the concrete slab, as well as the width across the road. For example, the representative rural local road is 102 mm (4 in) thick, with two 3.4 m (11 ft) wide lanes each, and two 0.6 m (2 ft) wide shoulders, whereas the urban interstate has 305 mm (12 in) of concrete, with three 3.6 m (12 ft) wide lanes in each direction, and two inner and two outer 3.0 m (10 ft) wide shoulders. Traffic is the other primary driver of the variation across structures, which also affects the fuel consumed due to roughness and traffic delay.

When looking at the life-cycle GWP contributions for each road type, the first notable feature is that cement production emissions are the largest contribution for every one of the twelve structures. The contribution of cement production ranges from 45% (for the urban interstate) to 72% (for the rural local road) of the total life-cycle emissions. The second largest contribution is fuel consumed from roughness in every case except for the rural minor collector, and local road, and the urban local road, where end of life disposal is the second largest contribution. For numerical results for all roadway classifications, see Tables A.4 through A.7 in Appendix A.

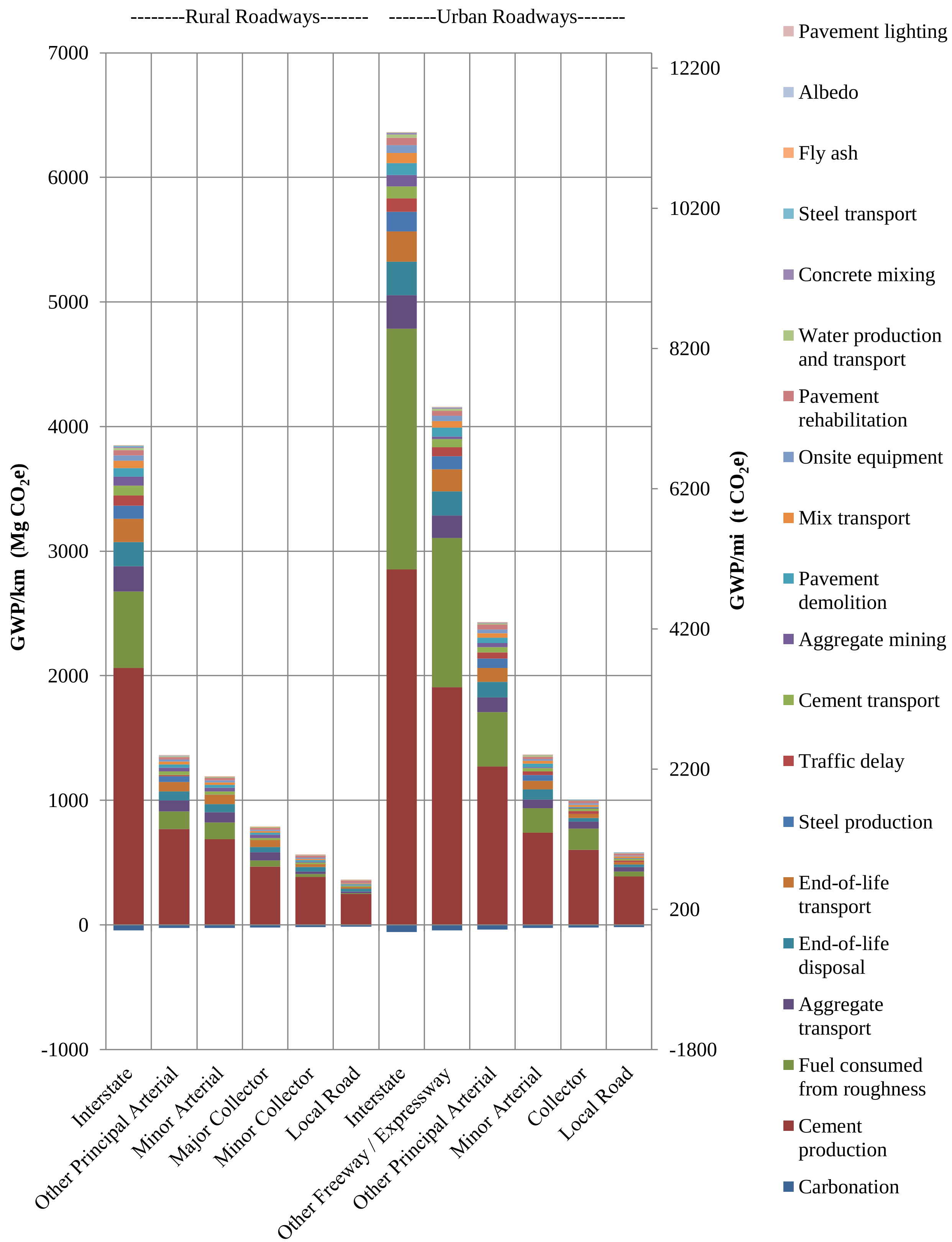

Figure 2.2 – Life-cycle GWP per km (mi) of new concrete pavements for twelve roadway classifications

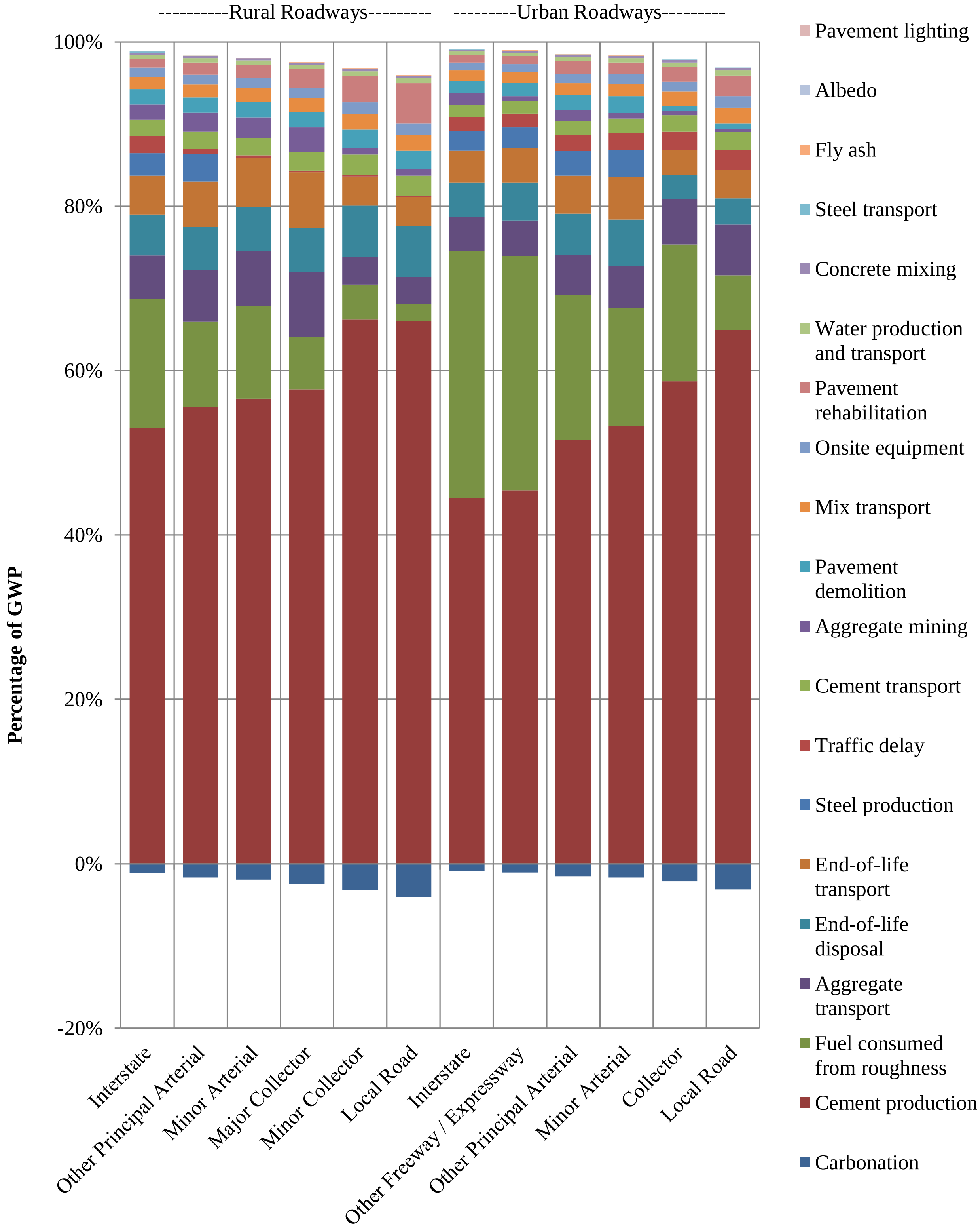

Figure 2.3 – Percent contribution to overall life-cycle GWP by life-cycle component for new concrete pavements for twelve roadway classifications

2.4.2 Time series emissions

While the majority of life-cycle GHG emissions are due to initial production and construction at the beginning of the analysis period, carbonation and fuel consumption due to roughness continuously affect the life cycle over the use phase, 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 interstates in Figures 2.4 and 2.5.

The initial emissions in year one (from materials extraction, production, and pavement construction) dominate the time series of emissions, at 67% of the total contribution for the rural interstate and 56% for the urban interstate. The second largest one-time contribution is from end-of-life demolition, transport, recycling and disposal, contributing 12% and 10% for the rural and urban interstate, respectively. This largely comes from transport and landfill emissions, which in reality are highly variable depending on waste management practices. While much of the concrete and aggregate base is modeled to transport to an aggregate stock yard, this assumption is conservative in cases where the pavement demolition coincides with reconstruction and the materials are reused on site. Additionally, landfilled concrete waste is normally buried in a carbon dioxide free environment, but waste management practices can take advantage of carbonation at the end of life, which is evaluated in the GWP reduction strategies of Section 2.6.

As can be seen in the figures, carbonation is more active initially after new construction and each rehabilitation activity, and then the effect slows. The reverse is true for roughness related emissions, which 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 GWP for both roads.

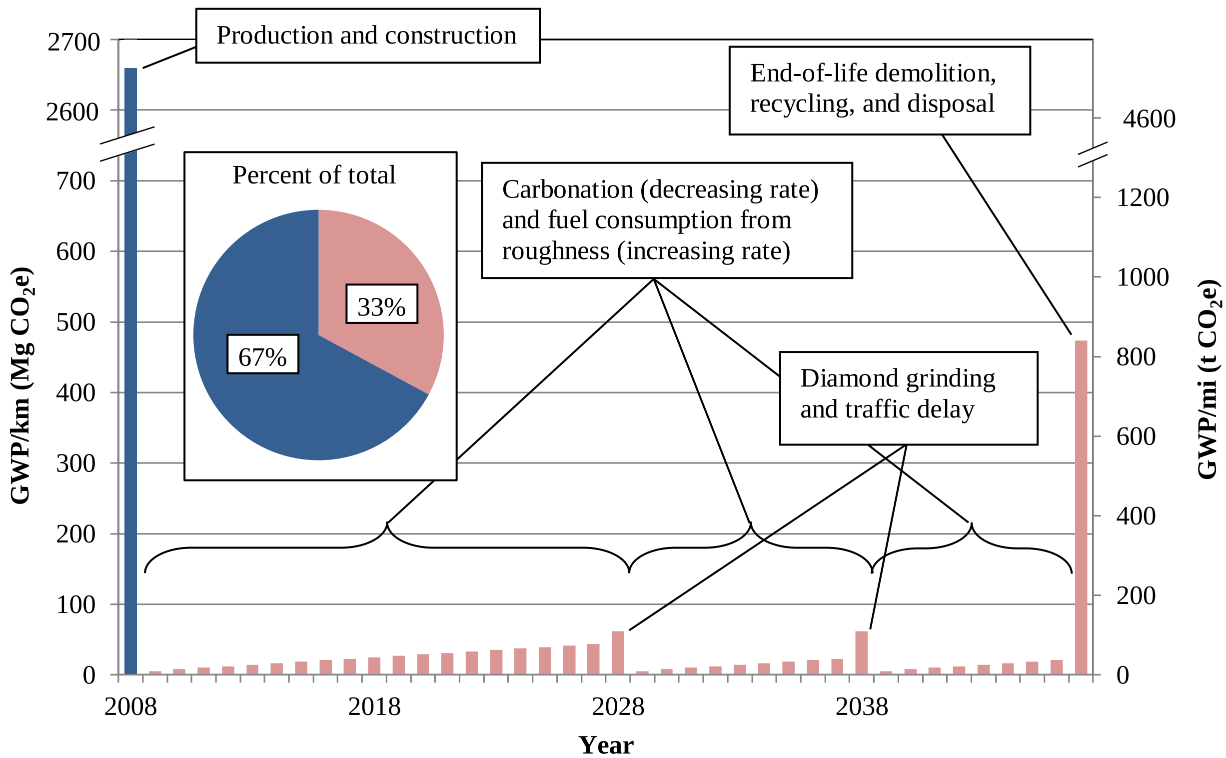

Figure 2.4 – Life-cycle GWP per km (mi) per year over the 40-year analysis period for a rural interstate built in 2008

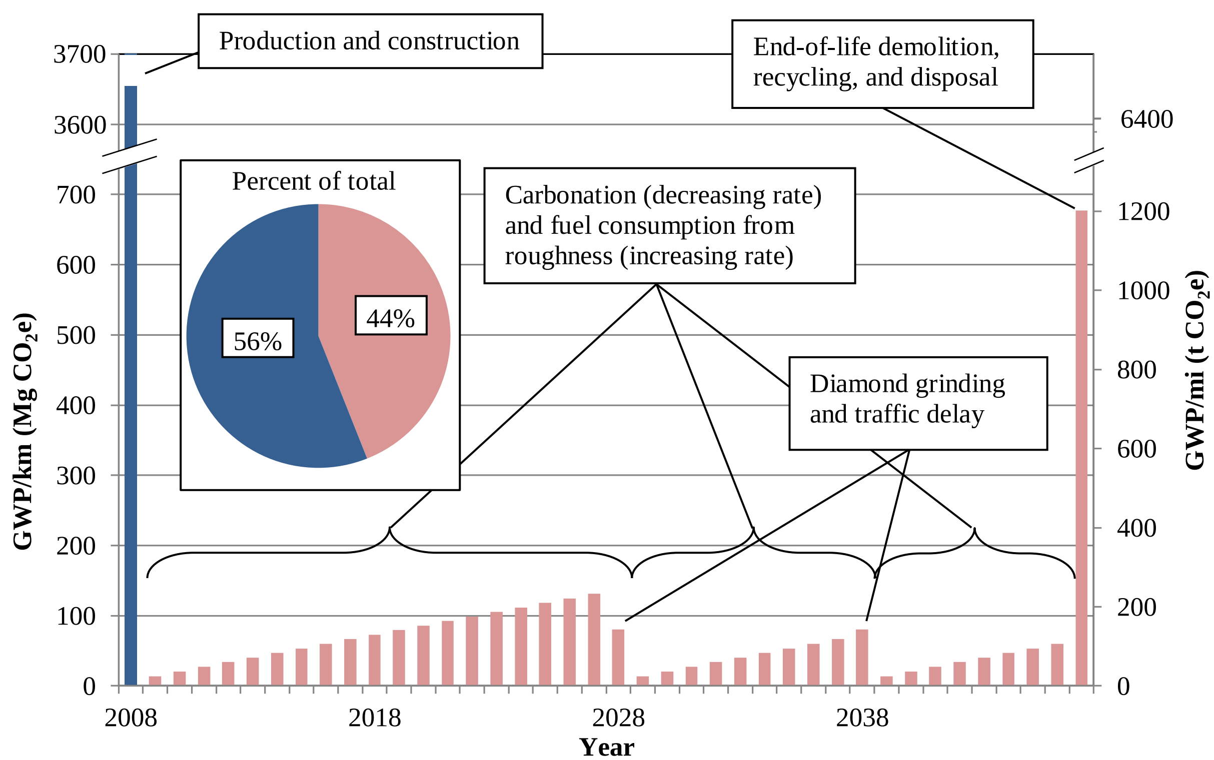

Figure 2.5 – Life-cycle GWP per km (mi) per year over the 40-year analysis period for an urban interstate built in 2008

2.4.3 Extrapolation Across the U.S. Network

The results representing each of twelve roadway classifications are extrapolated based on the number of lane-kilometers (lane-miles) of that classification in order to obtain a national estimate for the annual GHG emissions due to new concrete pavement construction. Table 2.6 shows the length of each of the five primary classifications, as well as the growth over time (adapted from FHWA (2009)). During this period, rural roads constitute approximately 43% of the entire network by length, and urban roads 57%. Adjusting for the extent of each roadway classification, as well as adjustments for lane counts and lane widths by using mean rather than mode values (see Table A.1 in Appendix A), the results in Figure 2.6 represent an estimate of the GHG emissions of all new concrete roads built on average per year in the U.S.

Table 2.6 – Extent of concrete network in 2008, and average annual growth rate for period of 1999–2008 in extent of entire network (FHWA 2009)

Roadway classification	2008 Length, km (mi)	Annual growth rate
Interstates/Other freeways	49,519 (30,770)	0.49%
Other principal arterials	73,033 (45,381)	0.47%
Minor arterials	65,654 (40,796)	0.60%
Collectors	113,941 (70,800)	0.03%
Local roads	224,442 (139,462)	0.39%

These emissions total 2.8 Tg CO_2e (3.1×10^6 t CO_2e) per year, or approximately 0.04% of total U.S. annual GHG emissions (EPA 2009). While this is a small proportion of overall national GHG emissions, this approximation does not account for a large proportion of the pavement network (namely asphalt pavements or asphalt rehabilitation on concrete pavements), nor the emissions from vehicle and goods damage, nor the potential impact of consequential effects of construction, such as induced road transport traffic. Understanding the order of magnitude of the GHG emissions for pavements provides further justification of the importance of improving pavement LCA studies.

In sum, the rural network contributes 1.3 Tg CO_2e (1.4×10^6 t CO_2e) per year (48% of total), and the urban network contributes 1.4 Tg CO_2e (1.6×10^6 t CO_2e) per year (52% of total). Urban interstates themselves contribute 0.5 Tg CO_2e (0.6×10^6 t CO_2e) per year (18% of total). The relatively large contribution from interstates is due to the massive structures and higher proportion of concrete lane-kilometers (lane-miles) relative to asphalt lane-kilometers (lane-miles) on this roadway classification. Collector roads on both rural and urban networks have the smallest contribution to the national emissions due to the fact that growth is negligible (0.03% per year) on this roadway classification.

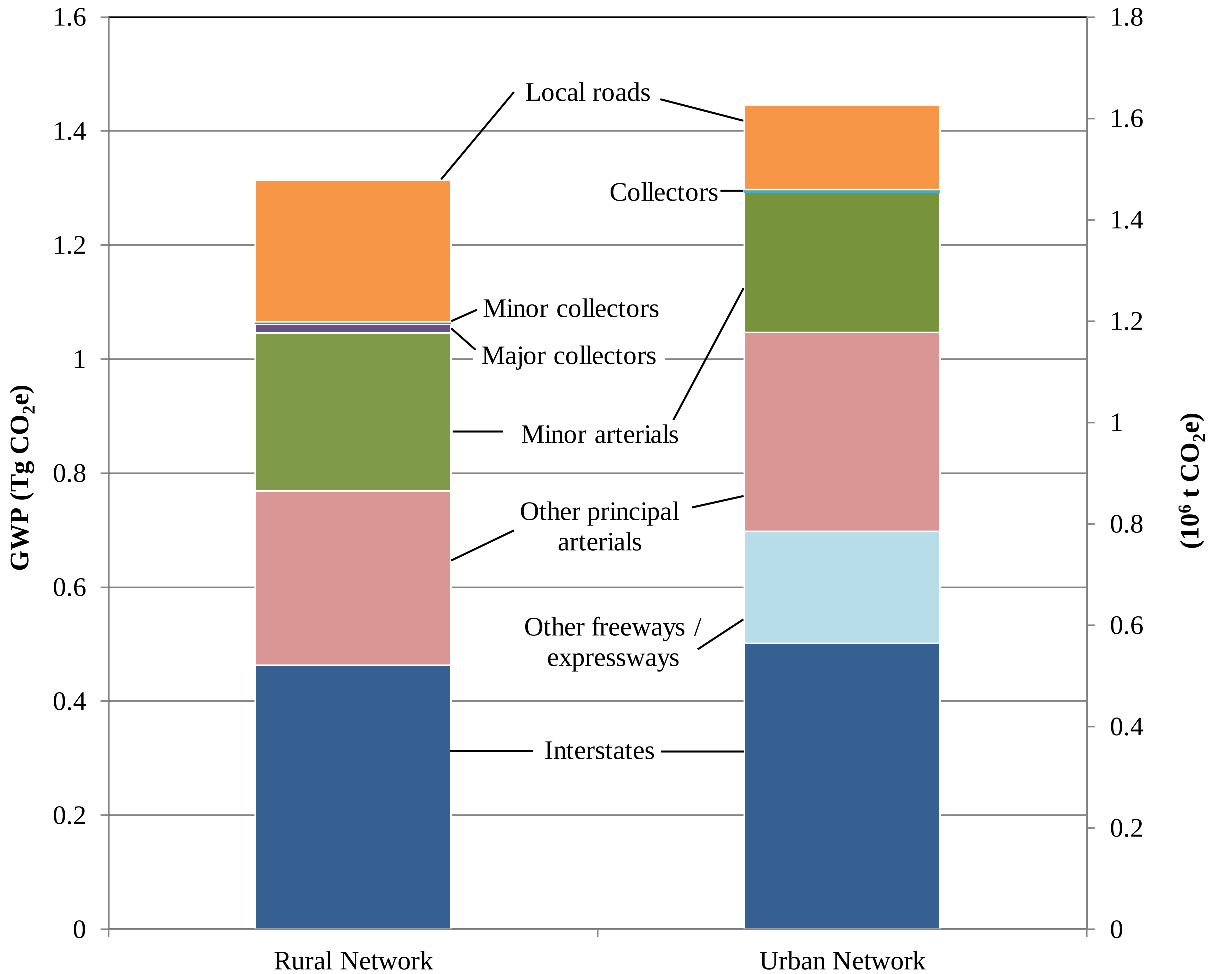

Figure 2.6 – Average annual life-cycle GWP from all new concrete pavements in the U.S. by roadway classification for 1999–2008

Figure 2.7 projects emissions 40 years into the future based on the average annual growth rate in the concrete pavement network. The first notable feature is that the accumulation of emissions is constant, because the average growth rate for each road is assumed to be constant into the future. 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. Of note is that this projection assumes that no improvements are made over time, when in reality, various energy efficiency, mix designs, and other advancements will change the annual footprint. It also annualizes the impact, thus smoothing the spiked emissions that occur during initial construction, rehabilitation, and EOL activities. For validation and details of the extrapolation procedure and results, see Loijos (2011).

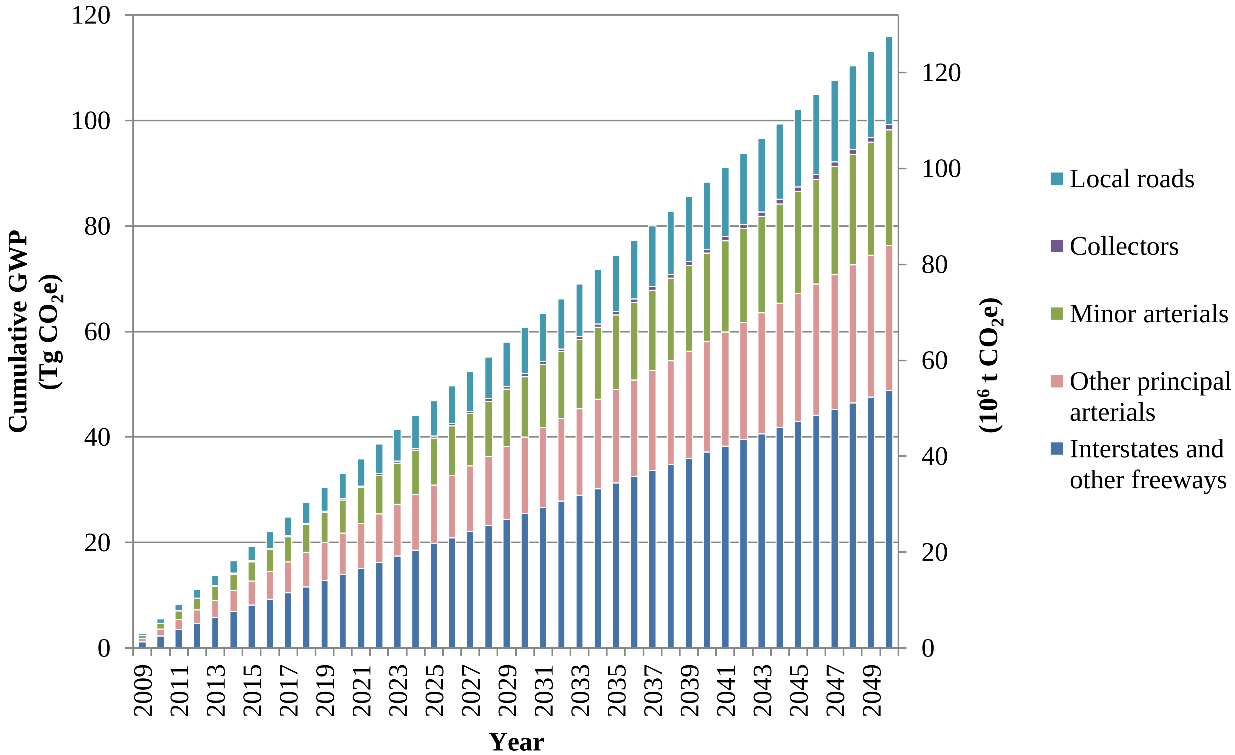

Figure 2.7 – Cumulative life-cycle GWP for all new concrete pavements in the U.S. for 2009–2050 on five major roadway classifications. Extrapolation based on average growth rate of each classification

2.5 Sensitivity Analysis

The LCA results presented in the previous sections use point values and average structures to estimate the GWP associated with concrete pavements. In order to provide a more robust assessment, sensitivity analyses are used to capture the uncertainty and variability of the input data. Three sensitivity aspects are explored: (1) traffic volume variability within each roadway classification; (2) timing of traffic closures; and (3) overall sensitivity to input parameters.

2.5.1 Traffic Volume

One of the variables that the results are most sensitive to is the traffic volume that the pavement structure supports. The results in Section 2.6 assume an average traffic volume and associated concrete pavement structure for each roadway classification, 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 is explained in Loijos (2011). The variability of GWP for each roadway classification in Figure 2.8 span between the first and fifth sextiles of AADT, which approximates one standard deviation from the mean. Some of the roadway classifications show large variability, including the rural interstate, urban interstate, urban other freeway/expressway, urban other principal arterial, and urban 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 asymmetry in many of the error bars.

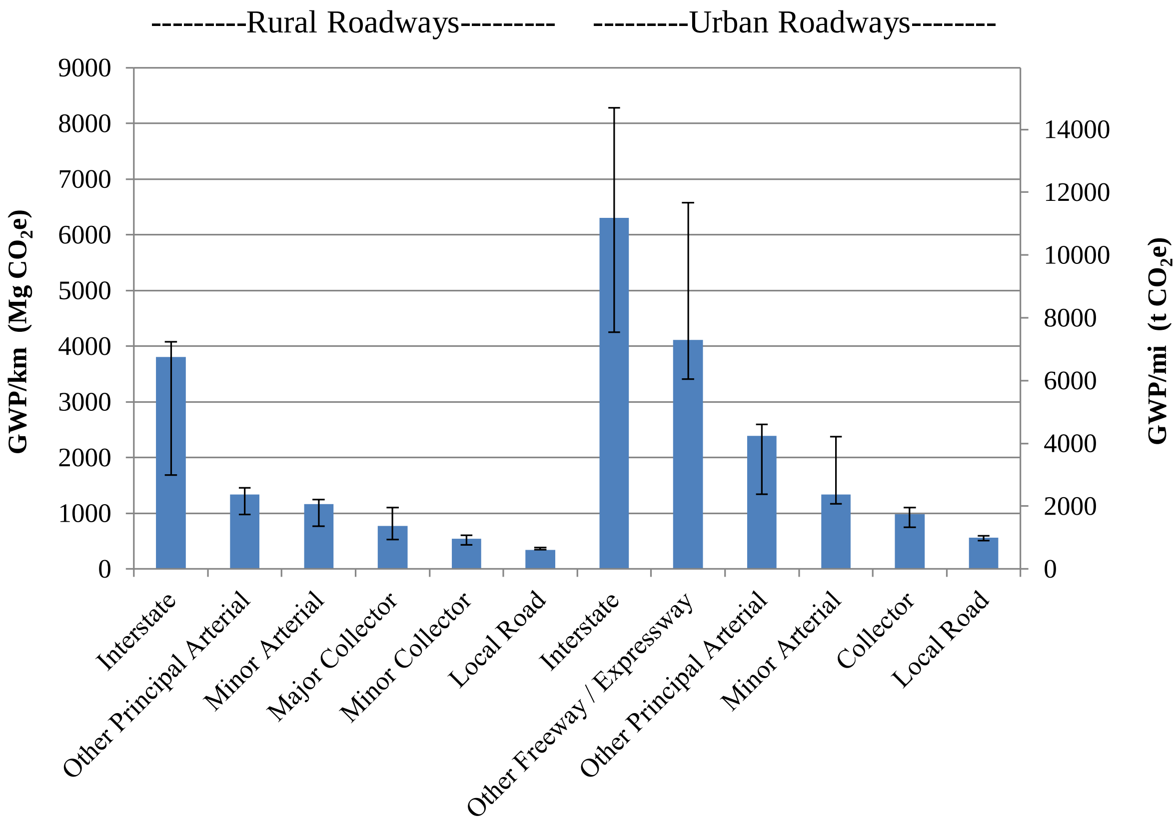

Figure 2.8 – Life-cycle GWP ranges per km (mi) for twelve roadway classifications based solely on variation in AADT on each classification

2.5.2 Traffic Closures

The results are also sensitive to lane closure timing. For the general assessment, it is assumed 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. In reality, daytime closures are sometimes unavoidable because of emergencies, budgetary constraints, demanding traffic conditions, or other complicating factors. The effect of daytime closures and the subsequent traffic queuing can have a dramatic impact on the life-cycle GHG emissions. Daytime closures (modeled using *RealCost*) are shown on the urban network in Figure 2.9, 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. The "other life-cycle components" comprise the results presented in Section 2.4.

It should be noted that this is for the purpose of demonstrating the potentially dramatic impact of suboptimal closure practices, and as such the modeled lane closure events occur during both rehabilitative activities and initial construction. The lane closure for initial construction applies to lane expansions on existing roads, as well as reconstruction, and is not representative of constructing an entirely new roadway. Only emissions that are due solely to rehabilitative activities are pertinent to new roadways, which constitute 7–8% of the overall traffic delay emissions for daytime closures on all roadway classifications, with the large majority occurring during initial construction.

On the urban interstate, consistently using daytime closures throughout the pavement life cycle results in an increase in GWP of 2,200 Mg CO_2e/km (3,900 t CO_2e/mi), and comprises 26% of the total life-cycle emissions for this case. On the urban other freeway/expressway, the representative traffic level is squeezed from four lanes down to two lanes, and 8 km long queues are predicted by *RealCost* during peak daytime traffic, which contributes an additional 6,500 Mg CO_2e/km (11,000 t CO_2e/mi) to the life cycle, constituting 61% of total emissions.

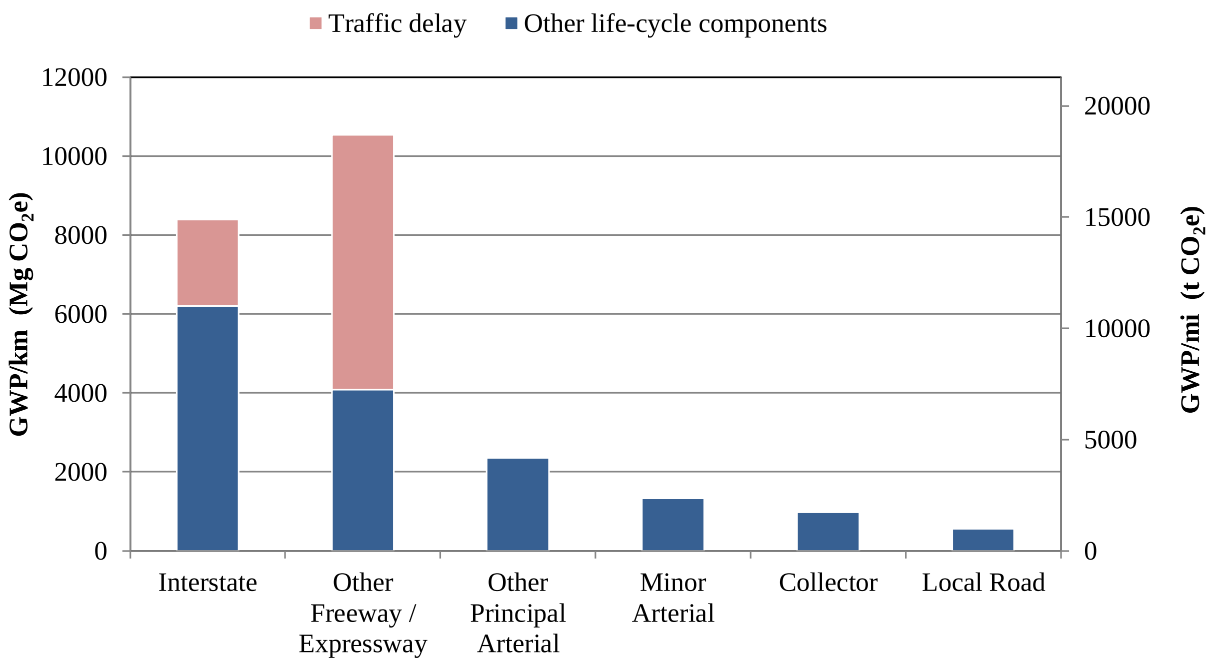

Figure 2.9 – Life-cycle GWP per km (mi) from daytime lane closures during new construction and rehabilitation activities on urban roadways

2.5.3 Overall Sensitivity

Based on variability in the input parameters discussed in Section 2.3, a sensitivity analysis of the results is performed. The results tend to be sensitive to certain set of parameters, but the sensitivity also depends on the roadway classification of concern. For example, the variable influence of climatic zone on pavement roughness is likely important to the total GWP 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 analyses, the traffic volume parameter was held fixed because of its heavy influence on the pavement design: the AASHTO '93 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.

Similarly, traffic delay is measured using *RealCost* and not included in the following sensitivity analysis. Hence, the sensitivity to traffic was analyzed separately in Sections 2.5.1 and 2.5.2.

The sensitivity analysis results are presented for the rural and urban networks in Figures 2.10 and 2.11. The graph shows the sensitivity of results to variation from the nominal value that is normally used to calculate the results. Although the distribution of parameter data may not be normal in all cases, a normal distribution was assumed to estimate the "sensitivity variation." It approximates one standard deviation from the nominal value ($\mu \pm \sigma$), such that approximately 68% of available data points are within this interval. In some cases the variation is estimated. Only those parameters which exceed an effect of 2% on a majority of the roadway classifications are included in the sensitivity 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). For the change in results displayed in Figures 2.10 and 2.11, the corresponding parameters, nominal value, and sensitivity variation are presented in Table 2.7.

Table 2.7 – Most influential model parameters, their nominal value, and the sensitivity variation (derived from available representative data (Loijos 2011))

Parameter Name	Nominal Value	Sensitivity Variation
Concrete thickness	*In Tables 2.1-2.2*	10%
Pavement albedo	0.33 (unitless)	8%
Outer shoulder width	*In Tables 2.1-2.2*	33%
Lane width	*In Tables 2.1-2.2*	9%
IRI @ 20 years	*In Table A.3*	11%
Car fuel increase from IRI	1.05%/1 m/km (0.02 in/mi)	25%
Cement emission factor	0.928 kg CO_2e/kg (0.928 lb CO_2e/lb)	8%
Agg. % by rail	27%	93%
Agg. truck distance	50 km (31 mi)	24%
# Rehabilitation events	2	22%

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 the international roughness index (IRI) over the first 20 years), while other parameters are more important on the smaller roads (e.g., outer shoulder width, carbonation rate, pavement albedo). This is primarily due to the fact that the parameters to which the results are more sensitive correspond to those life-cycle components that contribute a larger proportion of the overall emissions. In general, smaller roads are sensitive to parameters which relate to materials production, since this has a larger contribution to the total. They are also sensitive to use phase components that are driven by surface area, like carbonation and pavement albedo. Larger roads are sensitive to traffic-related parameters, since the roughness and traffic delay components comprise a larger proportion of overall emissions. There are also variations across roadway classifications that are due to different nominal values in the parameters. These include number and width of lanes, number and width of shoulders, lighting requirements, and roughness.

Figure 2.10 – Sensitivity of life-cycle GWP to ten most influential parameters on six rural roadway classifications

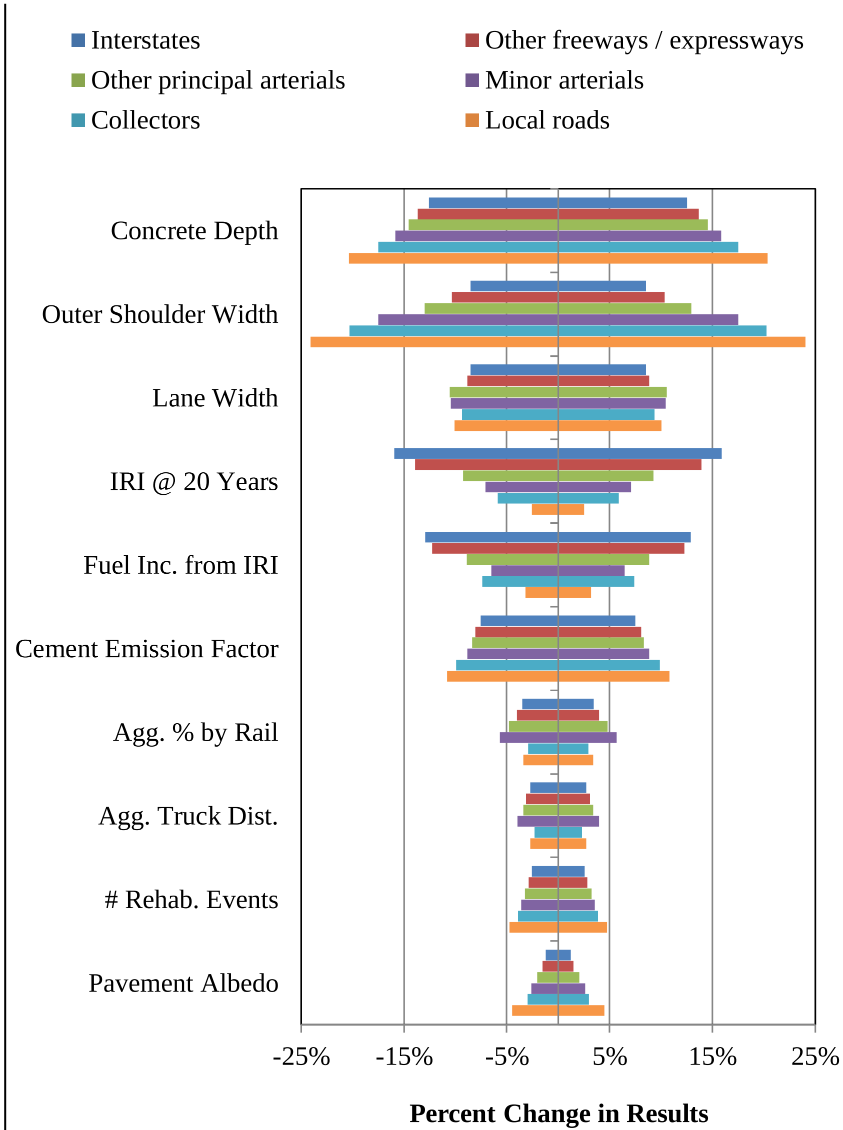

Figure 2.11 – Sensitivity of life-cycle GWP to ten most influential parameters on six urban roadway classifications

2.6 GHG Emission Reduction Opportunities

The LCA results presented in Section 2.5 provide a foundation to identify and evaluate opportunities for reducing the life-cycle GHG emissions of concrete pavements. Reductions in in GHG emissions can be achieved in various ways, including through material improvements and using less emission-intensive materials; using pavement designs that remove overdesigned thicknesses and features; and improving manufacturing and construction processes. This section explores four broad reduction approaches: (1) reducing embodied emissions; (2) increasing albedo; (3) increasing carbonation; and (4) reducing the impacts of PVI. Within each of these approaches, strategies can be identified that offer specific opportunities to reduce GHG emissions. Table 2.8 presents a list of some GHG reduction opportunities available for concrete pavements. It should be noted that this table is not meant to be an exhaustive set of options, but rather a demonstrative list of potential improvement pathways.

Table 2.8 – Potential GHG emission reduction strategies for concrete pavements

Reduction category	Strategy	More Information
Embodied emissions	SCMs: - fly ash* - GGBFS - silica fume - others	Section 2.6.1.1 and Tikalsky (2010)
	two-lift paving	CP Tech (2010a)
	Darwin-ME/MEPDG designs*	Section 2.6.1.6
	roller compacted concrete	CP Tech (2010b)
	virgin aggregate substitutes	Horvath (2004b)
	limestone additions	Thomas et al. (2010)
	reduced processing energy	Worrell and Galitsky (2008)
Albedo and urban heat island	white aggregate*	Section 2.6.1.2
	white cement	Levinson and Akbari (2002)
	GGBFS	Boriboonsomsin (2007)
	pervious concrete	Kaloush et al. (2008)
	photocatalytic cement	Guerrini (2010)
	two-lift paving (high albedo materials in top surface)	CP Tech (2010a)
Carbonation	EOL stockpiling*	Section 2.6.1.3
	EOL: embankments	Collins (2010)
	EOL: subbases	Collins (2010)
	pervious concrete	Haselbach and Ma (2008)
PVI	extra rehabilitation*	Section 2.6.1.4
	stringless pavers	CP Tech (2011c)
	improved smoothness stability	Perera et al. (2005)
	incentives for reduced initial smoothness	Perera and Kohn (2002)
	Stiffer pavement structures	Section 3

* evaluated in this research

This section consists of two parts: the first part 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 in Section 2.4.

2.6.1 Evaluation Methodology

Four distinct and one combined GHG reduction strategy scenarios are quantified in this research: reducing embodied emissions through fly ash replacement of cement; increasing albedo with white aggregates; increasing carbonation through end-of-life waste concrete management; reducing fuel consumption by adding an extra rehabilitation activity; and a combined scenario that evaluates all of these reduction strategies simultaneously.

A sixth, location-specific strategy is used to evaluate the effect that overdesign has on embodied emissions. This is evaluated as a separate case study due to the dependence of pavement design on climate conditions. A summary of key parameter data and assumptions is found in Table 2.10 at the end of this section.

Of note is that the chosen strategies are not meant to be an exhaustive set of options for reducing GHG emissions, but rather an exploratory set of opportunities. The objective is the quantify a limited set of strategies and demonstrate an approach that can later be used to evaluate a larger set of reduction strategies, such as those listed in Table 2.8. Also of note is that these reductions are based on average roadway dimensions and structures, thus lacking the project-specific inputs that are necessary to obtain more accurate and refined results. The intent is to provide estimates for a select number of generalized strategies in order to gain insight into the magnitude of possible GHG reductions.

2.6.1.1 Reducing Embodied Emissions: Increased Fly Ash

Embodied emissions are those released during the manufacturing and construction of paving materials. These emissions can be reduced by using less natural resources, substituting less emission-intensive materials, or otherwise reducing production emissions (e.g., more efficient processes). Concrete pavements can reduce embodied emissions in numerous ways, including optimizing mix and structure designs, using supplementary cementitious materials (SCMs), or continuing to switch from wet to dry kilns.

The embodied emissions reduction strategy explored here is increasing the use of a particular SCM—coal fly ash—in the concrete mix design. Fly ash is already widely used in the in the concrete industry, as noted by the 10% inclusion in the baseline mix. An increase from 10% to 30% fly ash replacement is modeled here to exemplify the possible reduction from one embodied emissions reduction strategy. An online database of state DOT practices reports that five of 19 agencies allow for up to 30% replacement of cement with fly ash, so this value is used to represent an aggressive-yet-realistic reflection of the potential use of fly ash in concrete pavements (ACPA 2011). Partial substitution of cement with fly ash at 10% and 30% replacement has been shown experimentally to increase the carbonation coefficient (the rate of carbonation) by about 5% and 10% respectfully (Lagerblad 2006), which is accounted for here.

2.6.1.2 Increasing Albedo: White Aggregates

Albedo measures the fraction of incoming solar radiation that is reflected by the pavement surface. Increasing albedo reduces the impacts from both the urban heat island effect and direct radiative forcing. While concrete naturally enjoys a relatively high albedo, improvements can be made to the concrete mix that increase the albedo even further. Materials that lighten the mix, such as white aggregates, white cement, and slag, generally correspond to increased albedo. More information on albedo and its relevance in the pavement life cycle is found in Santero et al. (2010).

As an example of albedo impact, white aggregates (both fine and coarse) are introduced into the pavement design. 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—a linear extrapolation of the pavement albedo's relationship to lighting demand is used to estimate the lighting needs on whitened pavement. This was based on extrapolating AASHTO average maintained illuminance (MI) recommendations for asphalt and concrete, and an assumed average albedo (α) 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 based only on selecting appropriate fine and coarse 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 2.12. The extrapolated illumination requirements are 9 lux for interstates, 6.5 lux for other freeways, 6.5 lux for other principal arterials, 6.9 lux for minor arterials, 4.9 lux for collectors, and 4.2 lux for local roads.

The albedo effect of the whitened pavement scenario is measured with reference to the average concrete albedo (0.325), so anything with higher albedo is attributed negative life-cycle emissions. Emission factors for the albedo effect are given in Section 2.3. An important note regarding this strategy is the local availability of white aggregates. In many locations, white aggregates may not be available, making this strategy only practical in certain regions. The results for this strategy (presented in Section 2.6.2) discuss the impact of transportation distances on the results. Additionally, the cost effectiveness of this strategy, which includes a sensitivity analysis on transportation distances, is discussed in Section 2.7.

Tan beach sand
(quartz, clay, minerals, micas)
0.45 albedo
0.20 mm (0.008 in) diameter

White rock
(plagioclase)
0.49 albedo
14 mm (0.6 in) diameter

Figure 2.12 – Fine (left) and coarse (right) aggregates used to increase pavement albedo (adapted from Levinson and Akbari (2002))

2.6.1.3 Increasing Carbonation: EOL stockpiling

Much of the CO_2 released during the calcination of cement can theoretically be captured through carbonation. Carbonation for an in-situ concrete pavement is minimal, penetrating only a few centimeters into the pavement over its service life and thus sequestering only a fraction of the

CO_2 release during calcination (e.g., see Section 2.4). Following Fick's law of diffusion, carbonation is expedited with increases in the surface-area-to-volume ratio—something that occurs when concrete pavements are crushed at their end of their service life. Crushed concrete is typically recycled as base, fill, or concrete aggregates. EOL carbonation arguably is most effective when exposed to the environment, but research shows that even buried crushed concrete sequesters a significant amount of CO_2 (Collins 2010). Regardless of the application, the recycling of concrete at the end of its life presents an opportunity for carbon sequestration.

The EOL option modeled here is the simple scenario of crushing and stockpiling the concrete for one year, during which time it assumed to sequester 28% of the initial CO_2 released from carbonation, or 155 grams of CO_2 per kilogram (310 lb CO_2/t) of cement in the mix (Dodoo et al. 2009). It should be noted that actual carbonation is uncertain and that the empirical data used for this estimate should be refined as more precise models become available. There are also practicality issues to consider, such as the willingness of DOTs and/or industry to stockpile recycled concrete for months at a time. This strategy represents only one option available at the end of life, although other options are likely similar in terms of the magnitude of emission reductions. Lastly, if this strategy was continuously applied for many pavements, the result would be an effective removal of some tonnage of aggregate supply from the available stock. The effect would be an induced demand for virgin aggregate to replace the lost stock—something that a more thorough LCA might consider within its boundaries.

2.6.1.4 Reducing Fuel Consumption: Extra Rehabilitation

Pavement-vehicle interaction can play an important role in the reduction of GHG emissions for pavements. For the modeled urban interstate roadway, the 79,000 vehicles per year have tailpipe emissions of over 10,000 Mg of CO_2e. Pavement characteristics which offer even slight fuel economy improvements can significantly decrease the GHG emissions associated with the pavement life cycle. PVI improvements can come in the form of reduced pavement roughness or reduced deflection in the pavement structure. The latter improvement is discussed in more detail in Section 3.

Reducing pavement roughness can be accomplished in various ways, including more frequent rehabilitation of the pavement surface. This scenario is evaluated by adding an extra pavement rehabilitation activity 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 1.0 m/km (63 in/mi), and secondly, completely uncarbonated concrete is exposed to the environment and carbonation resumes again at its faster, initial rate.

2.6.1.5 Combined GHG Emissions Reduction Strategy

This reduction strategy incorporates all four of the above scenarios, with the exception of the additional rehabilitation for the rural major collector, minor collector, local road, and the urban local road because these obtained no life-cycle GWP benefit. The model accounts for the interdependencies that exist between different strategies, such as the combined effect of an increased carbonation coefficient from fly ash substitution and an additional exposure of fresh concrete for accelerated carbonation that is due to the additional rehabilitation activity.

2.6.1.6 Case Study: MEPDG Design Optimization in Oxnard, CA

Long-term pavement performance (LTPP) data collected by the FHWA indicates that concrete pavements often last much longer than they were designed for initially. LTPP data for California, North Carolina, and Florida show concrete pavements that have supported up to ten times the traffic that they were designed to carry (CEMEX 2010). The Mechanistic Empirical Pavement Design Guide (MEPDG) model was developed in order to match pavement design with empirically measured performance, and calibrate the design procedure with regional, material, and temporal data, because under the AASHTO ’93 procedure it is difficult to accurately extrapolate the original data to different situations (Portland Cement Association 2009). In at least some cases, the AASHTO ’93 design procedure leads to overdesign, and the improvement MEPDG offers can also lead to reduced LCA impacts.

In order to evaluate the GWP of the more accurate MEPDG procedure, the same traffic and service life inputs that were used for the baseline (AASHTO ’93) designs were input into the MEPDG software. A moderate climate in Oxnard, California was assumed. The structure designs for six of the twelve roadway classifications are listed in Table 2.9 as compared to their AASHTO ’93 equivalents. MEPDG is primarily a high traffic volume design tool, and does not provide outputs of less than 178 mm (7 in) for the concrete slab thickness, so the low-volume classifications are excluded from this reduction scenario.

While a moderate climate was specifically chosen to show the potential GWP and cost benefits of MEPDG-derived designs in the present case study scenario, it must be noted that the results may differ in other climates. MEPDG’s ability to design for specific climate conditions can more accurately design to reach given serviceability requirements than the climate-independent AASHTO ’93 procedure.

Table 2.9 – MEPDG concrete pavement designs compared to AASHTO '93 equivalents for Oxnard, CA (SI units, see Table A.12 for U.S. units)

Rural Network			*Urban Network*		
Roadway class	AASHTO ‘93	MEPDG	Roadway class	AASHTO ‘93	MEPDG
Interstate	292 mm JPCP 152 mm base 38 mm dowels	229 mm JPCP 102 mm base 38 mm dowels	Interstate	305 mm JPCP 152 mm base 38 mm dowels	229 mm JPCP 152 mm base 38 mm dowels
Other Principal Arterial	203 mm JPCP 152 mm base 38 mm dowels	191 mm JPCP 102 mm base 25 mm dowels	Other Freeway / Expressway	249 mm JPCP 152 mm base 38 mm dowels	216 mm JPCP 152 mm base 38 mm dowels
Minor Arterial	191 mm JPCP 152 mm base No dowels	178 mm JPCP 102 mm base No dowels	Other Principal Arterial	216 mm JPCP 152 mm base 32 mm dowels	191 mm JPCP 102 mm base 32 mm dowels

Table 2.10 – Summary of key input parameters for reduction scenario analysis

Reduction scenario	Key parameters and assumptions
Fly ash substitution	30% replacement of cement; 5% increased carbonation rate (Lagerblad 2006)
White aggregate	Concrete α = 0.41; MI_{avg} = 9; 6.5; 6.5; 6.9; 4.9; 4.2 lumens/m^2
EOL stockpiling	Additional 155 g CO_2 / kg (0.155 pounds CO_2 / pound) cement sequestered at end of life (Dodoo et al. 2009)
Additional rehabilitation	Diamond grinding of 1 cm at year 10, 1 cm increased initial pavement thickness. Re-exposes fresh concrete for accelerated carbonation.
MEPDG design case study	Climate zone: Oxnard, CA. MEPDG-derived designs in Table 2.9

2.6.2 GHG Emission Reduction Results

The GHG reduction strategies are intended to provide DOTs, municipalities, and other stakeholders guidance as to effective approaches to design less GHG-intensive concrete pavements. The reductions for the discussed strategies are presented in Figures 2.13 and 2.14. The strategy with the highest GWP reduction depends on the roadway classification of concern. On urban interstates, increasing fly ash reduces the most GWP (670 Mg CO_2e/km, 1,200 t CO_2e/mi), whereas white aggregate offers higher reductions (albeit narrowly) on all structures with an AADT of less than 10,000 vehicles/day.

It is worth noting the impact of increased transportation distance that is likely associated with the white aggregate strategy. This strategy reduces GWP by 8% of the total on urban interstates (530 Mg CO_2e/km, 940 t CO_2e/mi) and up to 43% of the total on rural local roads (150 Mg CO_2e, 270 t CO_2e/mi). 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 roadway classification, the willingness to trade-off with increased aggregate transportation also varies. White aggregate (of albedo 0.45–0.49) gives a net GWP benefit for an urban interstates at transport distances up to 200 km (120 mi) by truck, 1,100 km (680 mi) by barge, or 1,700 km (1,100 mi) by rail. For a rural local road, there is a benefit up to about 850 km (520 mi) by truck, 3,800 km (2,400 mi) by barge, and 8,200 km (5,100 mi) by rail. This point is, however, sensitive to the durability of the pavement as well as the analysis period.

Also of interest is that the extra pavement rehabilitation strategy only benefits some roadways, 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 13% reduction in GWP occurs on high traffic urban interstates, the life-cycle GWP of rural local roads increases by 10%. There is a crossover point where this strategy becomes beneficial at an AADT of greater than approximately 2,500 vehicles per day.

Combining all four strategies, significant carbon reductions are obtained across all roadway classification. In the case of urban interstates, a 48% GWP reduction is obtainable by combining the four strategies, which amounts to a reduction of 2,400 Mg CO_2e/km (4,300 t CO_2e/mi). The reduction proportion that is achievable increases as traffic volume decreases: 70% reduced GWP is achieved on the rural local road. In this case, carbon that is sequestered through carbonation and light that is reflected from pavement albedo greatly reduce overall emissions.

The MEPDG strategy is presented separately due to its sensitivity to climate inputs. Figure 2.15 shows the results of MEPDG design procedure compared to the original AASHTO ’93 design procedure, which uses regional data from the moderate climate of Oxnard, CA. MEPDG does not offer design differences for low-traffic volume roadways, so these roadway classifications are omitted. Reductions in GWP are achieved in all six of the analyzed cases, from 8% on rural minor arterials to 17% on rural interstates.

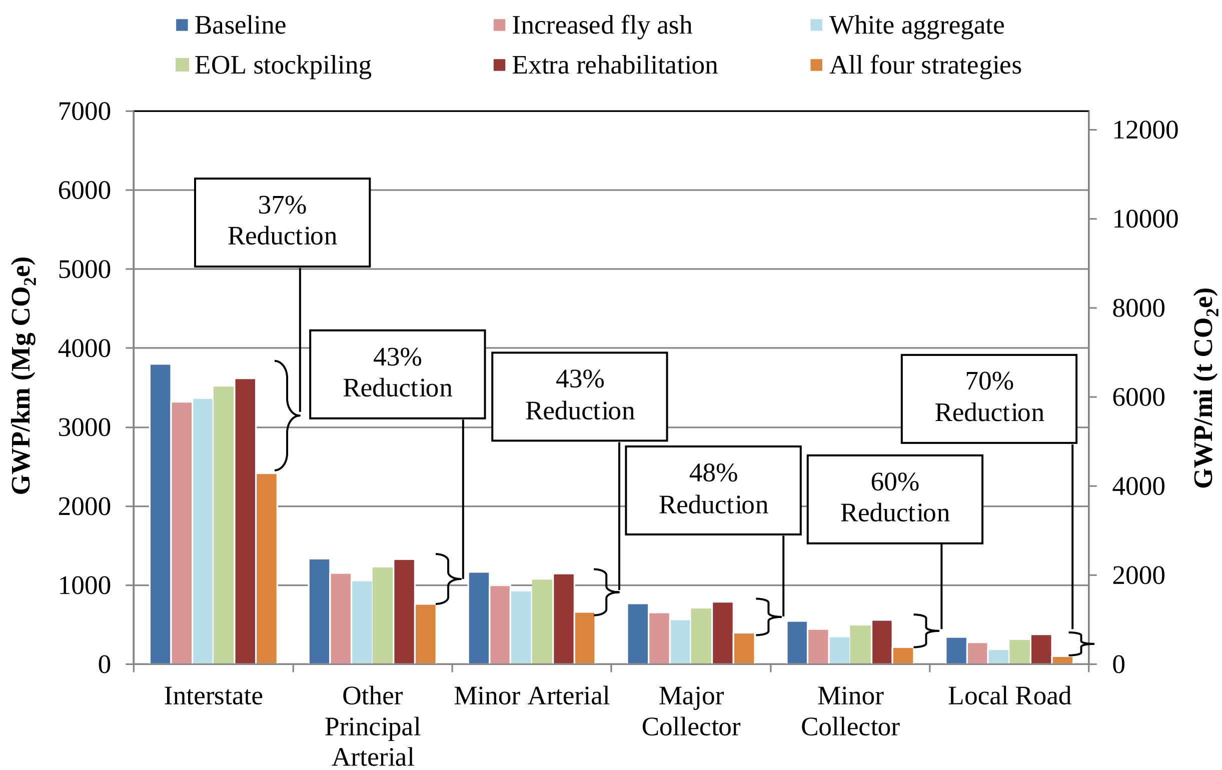

Figure 2.13 – Rural network opportunities: life-cycle GWP per km (mi) by roadway classification and by GHG reduction strategy. Overall reductions are shown for combining all four strategies on each roadway classification

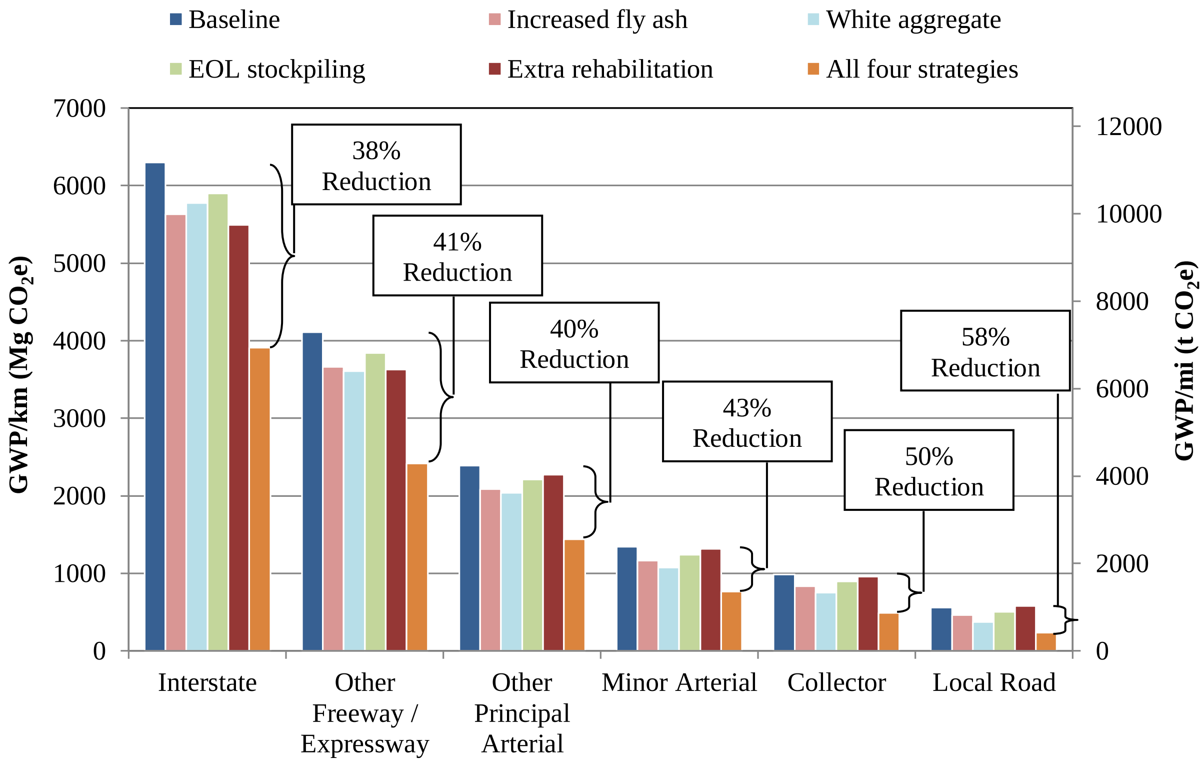

Figure 2.14 – Urban network opportunities: life-cycle GWP per km (mi) by roadway classification and by GHG reduction strategy. Overall reductions are shown for combining all four strategies on each roadway classification

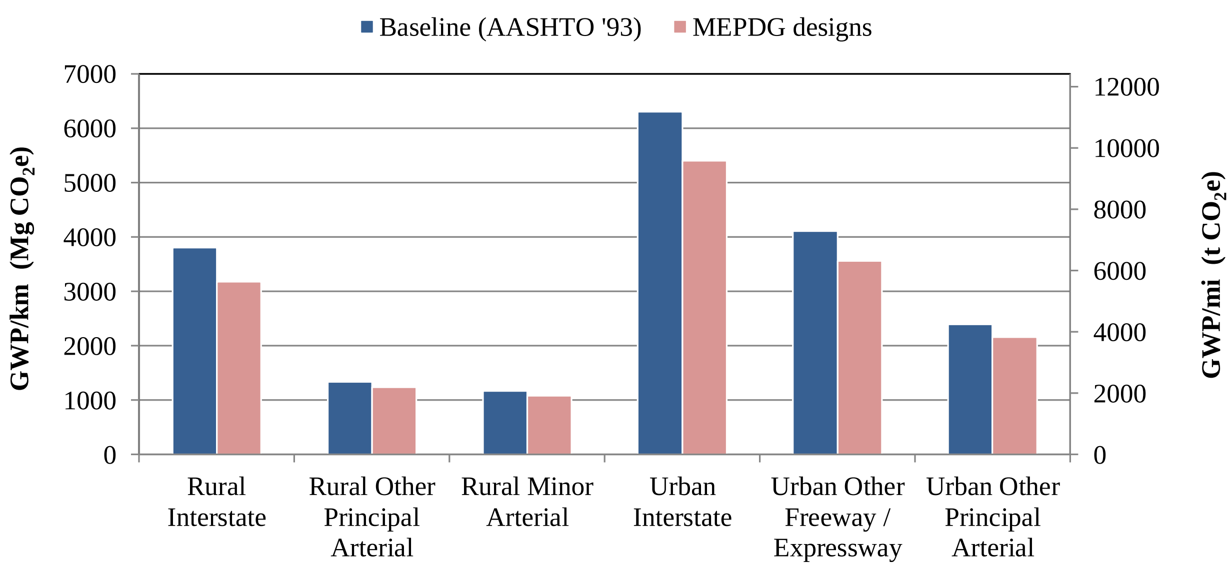

Figure 2.15 – Case study GHG reduction strategy: life-cycle GWP per km (mi) for MEPDG procedure compared to AASHTO '93 design procedure on three rural and three urban roadway classification in Oxnard, CA

2.7 Cost-Effectiveness Analysis

Economics provide the critical link that helps implement environmental impact reduction strategies into DOT decision-making frameworks. While most DOTs are interested in reducing their GHG footprint, the primary goal remains to provide maximum pavement performance within budgetary constraints. Reaching environmental targets necessarily becomes a second-order priority. In order to effectively integrate GHG reduction strategies into DOT decision-making, it is essential to appreciate that reductions must be achieved at minimal costs. One method of evaluating the potential of reduction strategies is through the use of cost-effectiveness analysis.

Cost-effectiveness analysis (CEA) is most commonly associated with the health and medicine fields, where it is used to evaluate the cost of different interventions with respect to their ability to increase quality of life (Gold 1996). Applying the concept to pavements and GHG emissions, reduction strategies can be evaluated not only on their reduction potential, but also the relative cost of that reduction. Equation 2.1 provides the basic relationship between costs, emissions, and cost effectiveness (CE). The "alt" and "base" subscripts refer to the cost of the reduction alternative case and the base case, respectively.

[2.1] $$CE_{alt} = \frac{cost_{alt} - cost_{base}}{emmissions_{alt} - emissions_{base}} = \frac{\Delta costs_{alt-base}}{\Delta emissions_{alt-base}}$$

The outputs from an LCA determine the values for the denominator of Equation 2.1; the numerator is determined through economic analysis. Following established LCCA protocols, the absolute cost of each strategy is not necessary to compute if the difference between the base and reduction strategy cases is known. Since many cost inputs will be identical between alternatives (e.g., construction processes, mobilization, unit costs), the demand for data is significantly reduced. Practitioners can focus on the differences between designs rather than calculating comprehensive, but largely irrelevant, absolute costs.

It is helpful to view these results with respect to the estimate price of carbon. Currently, the European Union Emissions Trading Scheme places the market value of carbon at \$19/Mg (\$17/t) (Point Carbon 2011). Alternatively, the Stern Review estimates that the social cost of carbon at \$85/Mg (\$77/t) under the business-as-usual trajectory, and between \$25–\$35/Mg (\$23–\$32/t) under a reduced emissions trajectory (Stern 2007). More recently, the Australian government announced a national carbon tax of approximately \$25/Mg (\$23/t) beginning in 2012 (Gillard et al. 2011). Regardless of the exact price of carbon, understanding the order of magnitude helps contextualize the CEA results. Reduction strategy costs that are comparable with (or below) the current carbon valuations are more likely to be considered "cost effective" from an agency or industry perspective.

Table 2.11 provides a summary of parameters that help describe the fundamental purpose, assumptions, and data associated with an individual CEA. Both costs and emissions are subject to uncertainty and variability, so proper transparency is critical in the reporting of methods, calculations, and results. Identifying key drivers in the CEA and conducting sensitivity analyses on those drivers helps convey the expected range of results. When performing generalized, non-project specific analyses, presenting a range of values rather than a single point value is done to capture uncertainty due to price volatilities and variability in emissions throughout the life cycle of the present pavement classifications.

Table 2.11 – Parameters and framework for CEA of GHG reduction strategies

Property	Description
Reduction category	Approach to reducing GHG emissions
Scenario	Specific strategy explored
Key driver(s)	Primary parameters which dictate the emissions and costs
Key cost(s)	Important unit costs and cost parameters
Emission range	GWP for evaluated scenario based on LCA results
Cost range	Cost(s) for evaluated scenario
Cost effectiveness range	Range of cost effectiveness values, measured in \$/Mg CO_2e saved (or equivalent)
Most cost effective (MCE)	Roadway classification which provides best cost effectiveness
Sensitivity parameters	Parameters and value ranges evaluated in sensitivity analysis. Sensitivity parameters often correspond with one or more key drivers.
Sensitivity of MCE	Range of cost effectiveness values for the determined best application

2.7.1 CEA Scenarios and Data

The GHG reduction strategies presented in Section 2.6 are evaluated for their cost effectiveness. Like with the reduction previous reduction analysis, it is important to note that these strategies and results are based on average roadway and structural data. This provides useful insight into the economic feasibility of the evaluated strategies for generalized scenarios, but lacks the accuracy that a project-specific analysis would provide. Sensitivity analyses are performed for selected parameters in order to estimate a range of expected costs. A summary of the strategies and the sensitivity parameters are presented in Table 2.12. Table 2.13 summarizes the cost and other data used in the CEA. The emissions data comes from the LCA presented in Section 2.6.

Table 2.12 – Description of CEA scenarios and sensitivity analyses

Strategy	Category	Description	Sensitivity analyses
Increased fly ash	Embodied emissions	Replacement of cement with fly ash costs.	- Fly ash unit cost
White aggregate	Albedo	Transportation costs associated with increased hauling distance.	- increased haul distance for white aggregates
EOL stockpiling	Carbonation	Carrying costs associated with storing crushed concrete aggregate	- Annual carrying cost - Exposure/storage time
Extra rehabilitation	Fuel consumption	Grinding of mainline concrete surfaces	- Grinding unit cost - Concrete unit cost
MPEDG case study	Embodied emissions	Reduction of concrete and base thicknesses	- Concrete unit cost - Base unit cost

Table 2.13 – Costs and other data used to conduct the CEA for the GHG emission reduction strategies (SI units, see Table A.13 for U.S. units)

Parameter	Best estimate	Low estimate	High estimate	Reference (if applicable)
Cement ($/Mg)	$102			USGS (2009)
Fly ash ($/Mg)	$50	$25	$65	Tikalsky et al. (2011)
Truck transport ($/Mg-km)	$0.10			
Extra aggregate haul (km)	50	0	200	
Recycled concrete value ($/Mg)	$7.43			USGS (2008)
Annual carrying cost (%/Mg/yr)	25%	20%	40%	Hendrickson (2008)
EOL carbonation duration (yr)	1	0.3	30	
EOL carbonation (% of calcination)	28%	20%	44%	Doodoo et al. (2009)
Grinding cost ($/m^2)	$4.31	$4.00	$5.00	Caltrans (2011)
Concrete pavement ($/m^3)	$212	$151	$273	Caltrans (2011)
Aggregate base ($/m^3)	$83	$51	$114	Caltrans (2011)
Steel dowel bar ($/m^3)	$165			USGS (2010)

2.7.2 CEA Results

The cost effectiveness of the GHG reduction strategies are shown in Figures 2.16 and 2.17. The solid bars represent the results using the best-estimate data shown in Table 2.13; the error bars represent the sensitivity to the low- and high-estimate data. Table 2.14 provides a synthesis of the results. The cost effectiveness using the best estimate data range from roughly (-$600)/Mg CO_2e saved ((-$540)/t CO_2e saved) for the MEPDG case study on urban interstates to over $1,000/Mg CO_2e saved ($910/t CO_2e saved) for extra rehabilitation on rural principal arterials. This range is broadened even further when the low and high estimates are considered. Cost effectiveness also varies between roadway classifications, indicating that the economically-preferred reduction strategy may shift based on the intended application. Note that for clarity purposes, the y-axis stops at $1,000/Mg CO_2e saved ($910/t CO_2e saved) even though some points are above that threshold. Strategies at that cost magnitude are significantly higher than estimated carbon prices and are thus considered to be above reasonable cost-effectiveness limits.

The replacement of cement with fly ash is a well-known and highly utilized strategy to reduce both emissions and costs. The results reflect this concept in the form of negative cost-effectiveness values for each of the roadway classifications. The best-estimate values range from (-\$43)–(-\$34)/Mg CO_2e saved ((-\$23)–(-\$15)/t CO_2e saved). Sensitivity to the price of fly ash broadens the range to (-\$71)–(-\$27)/Mg CO_2e saved ((-\$12)–(-\$37)/t CO_2e saved). The results also show that the cost effectiveness differs slightly between the roadway classifications, with high-volume roadways (i.e., those with thicker concrete layers) having a moderately better cost effectiveness. This slight nonlinearity is due to the fact that the carbonation rate increases with the addition of fly ash (Papadakis 2000). Regardless of this slight difference, the magnitude of value—roughly (-\$40)/Mg CO_2e saved ((-\$36)/t CO_2e saved)—is an important indicator describing the cost effectiveness of fly ash replacement.

The driving force behind the cost effectiveness of using white aggregates to increase albedo is transportation distance. Assuming an extra haul distance of 50 kilometers (31 miles), the cost effectiveness range is \$41–\$170/Mg CO_2e saved (\$37–\$150/t CO_2e saved), with the best applications being on low-volume roadways. Locally available white aggregate results in no additional cost (\$0/Mg (or t) CO_2e saved), while long-distance hauling drastically decreases the effectiveness of this reduction strategy (\$180–\$1,200/Mg CO_2e saved, or \$160–\$1,100/t CO_2e saved). Since albedo is a surface property, pavements with high surface-area-to-concrete-thickness ratios will have better cost effectiveness: only the fine and coarse white aggregates at the top of the structure will contribute to the albedo reduction. Concrete overlays and two-lift concrete structures could take advantage of this concept by utilizing the albedo benefits of white aggregate while minimizing the "wasted" white aggregates in the structure.

Both the amount and cost of CO_2 sequestration by EOL stockpiling depends on the length of time the crushed concrete is exposed to the environment. Given a one year exposure, concrete is estimated to sequester an additional 28% of the calcinated CO_2 (Doodoo et al. 2009). With an annual carrying cost of 25% of the recycled concrete value, one year of EOL stockpiling has a cost effectiveness of \$100/Mg CO_2e saved (\$91/t CO_2e saved), which is equal across all roadway classifications. The rate of carbonation diminishes over time, resulting in reduced cost effectiveness as the length of exposure increase: while more CO_2 is sequestered, the mass per year is reduced. A four month exposure time and an annual carrying cost of 20% costs \$33/Mg CO_2e saved (\$30/t CO_2e saved), while a 30-year exposure time with an annual carrying cost of 40% (almost complete carbonation) near \$3,000/Mg CO_2e saved (\$2,700/t CO_2e saved).

Adding an extra rehabilitation is a potentially cost-effective method of reducing emissions for high-volume roadways, although the results presented here seem to suggest otherwise. Since the roadways modeled in this research are for typical conditions across twelve classifications, many outlying scenarios—such as those with high traffic volumes and/or high IRI values—are not fully captured by the scope of this research. Adding an extra rehabilitation for urban interstates has a cost effectiveness of \$180/Mg CO_2e saved (\$160/t CO_2e saved), but are only modeled for the average traffic of 79,000 vehicles per day. With volumes ranging up to 130,000 and higher on some urban interstates, an extra rehabilitation could provide significantly better cost effectiveness for pavement under different conditions. Moreover, the roadways modeled here are in relatively good condition at year 10, which is when the extra rehabilitation is assumed to occur: the IRI at year 10 is 1.2 m/km (75 in/mi), with grinding assumed to reduce the roughness to 1.0 m/km (63 in/mi). Roadways with higher pre-rehabilitation IRI values will benefit more from grinding, leading to larger emission reductions and better cost effectiveness.

The MEPDG case study shows significant potential as a cost-effective method of reducing GHG emissions. Avoiding overdesign essentially reduces the thicknesses of the concrete and/or base layers, thus mitigating the costs and emissions from the associated materials and processes. For the Oxnard case study described in Section 2.6, the best-estimate cost effectiveness ranged from (-\$620)–(-\$370)/Mg CO_2e saved ((-\$560)–(-\$340)/t CO_2e saved), indicating that emission reductions are achieved alongside significant cost savings. Sensitivities to material prices broadened the range ((-\$790)–(-\$260)/Mg CO_2e saved, or (-\$720)–(-\$240)/t CO_2e saved), but indicated the same magnitude of cost effectiveness. As with the fly ash scenario, the results show that higher-traffic roadway classifications appear to offer better cost effectiveness, but this is likely due to the assumption that construction cost is linearly proportional to material unit prices. Further research and project-level estimates can offer more exact calculations regarding the cost effectiveness of structure optimization.

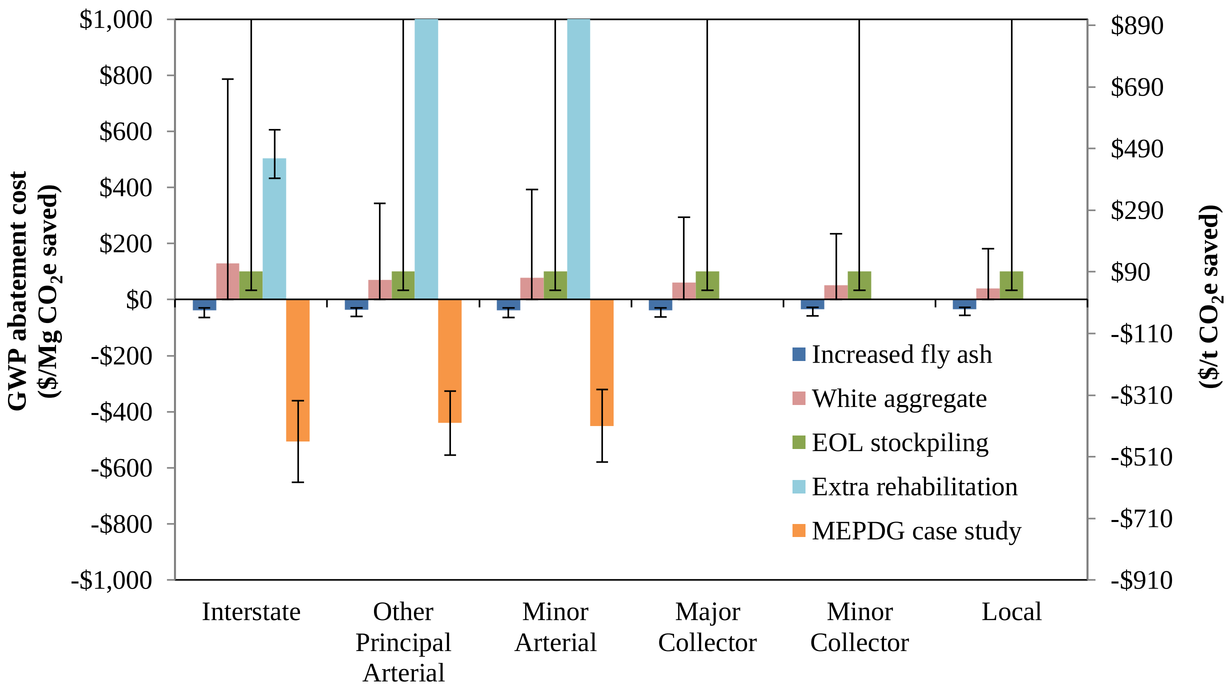

Figure 2.16 – Cost effectiveness of five GHG reduction strategies for rural roadways using undiscounted costs (solid bars represent best-estimate data, and min and max represent low and high data, respectively)

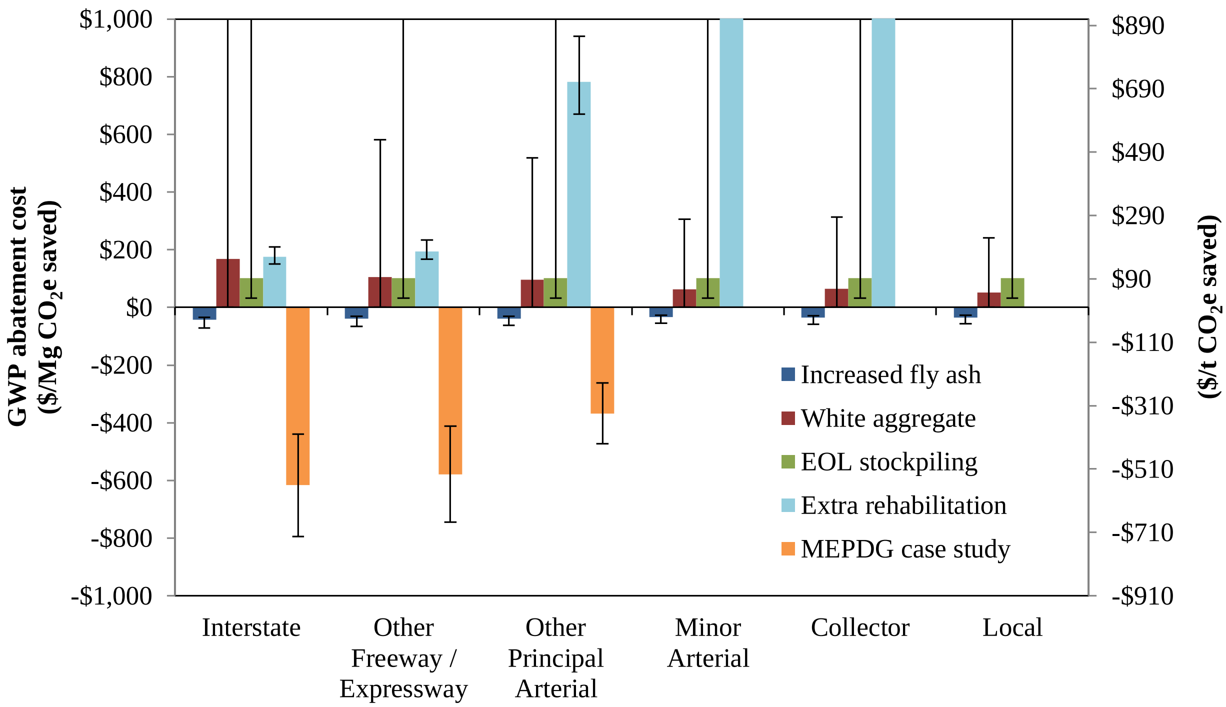

Figure 2.17 – Cost effectiveness of five GHG reduction strategies for urban roadways using undiscounted costs (solid bars represent best-estimate data, and min and max represent low and high data, respectively)

Table 2.14 – Summary of inputs and results for the cost effectiveness of GHG reduction strategies (SI units, see Table A.13 for U.S. units)

	Increased fly ash	White aggregates	EOL stockpiling	Extra rehabilitation	MEPDG case study
Reduction category	Embodied emissions	Albedo	Carbonation	PVI	Embodied emissions
Key assumption(s)	10% → 30% fly ash replacement	- 0.19 albedo increase - 50 km extra distance	1-year EOL exposure	Additional grinding at year 10	Equivalent design life as AASHTO '93 design
Key driver(s)	- Fly ash cost* - Fly ash content	- Longer transportation distance* - Albedo increase of white aggregates	- Exposure time* - Annual carrying cost*	- Grinding cost* - Concrete cost* - Grinding schedule - "Roughness → rolling resistance" factor	- Material unit costs* - M&R schedule - Extent of overdesign
Key cost(s)	Fly ash cost: $50/Mg	Transportation unit cost: $0.10/Mg/km	Annual carrying cost: 25% of market value	- Grinding cost: $4.30/m^2 - Concrete cost: $212/m^3	- Concrete cost: $212/m^3 - Base cost: $83/m^3
Emissions saved (Mg CO_2e saved/km)	64–670	150–460	32–410	10–810	89– 910
Cost range (per km)	(-$29,000)–(-$2,200)	$6,000–$77,000	$3,200–$42,000	$35,000–$140,000	(-$560,000)–(-$40,000)
Cost effectiveness range ($/Mg CO_2e saved)	(-$43)–(-$34)	$41–$170	$100	$180–$7,400	(-$620)–(-$370)
Most cost effective (MCE)	Urban interstates	Rural local roads	Equal across all classifications	Urban interstates	Urban interstates
Sensitivity parameters	- Fly ash cost: $25–$65/Mg	Extra transportation distance: 0–200 km	- Exposure time: 4 month, 1 year, 30 years - Annual carrying cost: 20–40%	- Grinding cost: $4–$5/m^2 - Concrete cost: $151–$273/m^3	- Concrete: $151–$273/m^3 - Base: $51–$114/Mg
Sensitivity of MCE ($/Mg CO_2e saved)	(-$71)–(-$34)	$0–$180	$33–$3,000	$150 –$210	(-$790)–(-$440)

* indicates that a sensitivity analysis is conducted for this driving parameter

2.7.3 Discounting

One of the most influential elements of any LCCA is the discount rate. The discount rate captures the time value of money and determines the present value of future costs. In general, the FHWA (Walls and Smith 1998) recommends using discount rates published in the most current version of the White House Office of Management and Budget (OMB) Circular A-94 (OMB 2010). Even with that guidance, a 2008 survey found that there is no universal agreement upon the discount rate value to be used for pavement projects: state agencies adopt discrete real rates ranging from 3% to 5.3%, while a minority of states used either sensitivity or probabilistic analyses to address the uncertainty regarding the rate (Rangaraju et al., 2008). To account for both the variability and uncertainty of the discount rate, this research conducts a sensitivity analysis for a range of values, encompassing the current OMB rate (2.3%), typical DOT values (3–5%), and undiscounted costs (0%).

The suitability and execution of discounting in a CEA depends on the timing of the evaluated reduction strategy. For evaluation of new and reconstructed pavements, discounting should be applied based on established FHWA procedures for conducting an LCCA. For instance, when evaluating the cost effectiveness of EOL stockpiling, a discount rate should be applied to account for the time value of money. Since EOL stockpiling costs occur 40+ years after initial construction, the present discounted value is a better measure of agency cost for that activity.

Reduction strategies for in-situ pavements may not need to consider discounted costs in the CEA. While the LCA results are tailored toward new and reconstructed concrete pavements, some of the reduction strategies themselves can be applied to existing pavements. In particular, the extra rehabilitation and EOL stockpiling are strategies that can be used to decrease the GHG emissions for pavements that are currently in use. For example, a to-be-demolished pavement can use EOL stockpiling to reduce its emissions, but the costs should be discounted only for the time period that the recycled concrete is stockpiled, which is probably one year or less.

Figures 2.18 and 2.19 show the CEA results for the best estimate values using a discount rate of 2.3%. The error bars show the sensitivity to a 0% discount rate (which is equivalent to the results presented in Figure 2.16 and Figure 2.17) and a 5% discount rate. The increased fly ash, white aggregate, and MEPDG case study scenarios all rely on changes during initial construction, so discounting does not affect the cost effectiveness. EOL stockpiling and the extra rehabilitation occur in the future, resulting in a more favorable cost effectiveness for these strategies when evaluated during the initial construction year. With a 2.3% discount rate, EOL stockpiling drops from the undiscounted value of \$100/Mg CO_2e saved (\$91/t CO_2e saved) to \$39/Mg CO_2e saved (\$35/t CO_2e saved). Using a discount rate of 5%, the cost effectiveness is further improved to roughly \$12/Mg CO_2e saved (\$11/t CO_2e saved). The present value of extra rehabilitation is also reduced, from \$180/Mg CO_2e saved (\$160/t CO_2e saved) for the undiscounted cost effectiveness to \$140/Mg CO_2e (\$130/t CO_2e saved) using a 2.3% discount rate and to \$110/Mg CO_2e saved (\$100/t CO_2e saved) using a 5% discount rate.

This analysis focuses on agency costs and thus uses discount rates as they are typically employed in DOT decision-making frameworks. Another approach is to use a social discount rate, which is often preferred when considering the social cost of carbon emissions. The *Stern Review* uses a near-zero social discount rate when evaluating climate change impacts (Stern 2007), although Nordhaus (2007) argues it should be higher to better represent market data and comply with current economic models. McKinsey & Company use a 7% social discount rate when analyzing abatement costs (Creyts et al. 2007). The IPCC discusses the lack of consensus around this issue, both with respect to the appropriate value as well as the prospect of time-declining rates (IPCC 2007). In addition, this CEA uses an agency perspective on cost abatement, thus adopting the LCCA approach that DOTs currently use in their decision-making process. However, many abatements analyses (such as McKinsey & Company) use levelized costs, particularly in the field of energy improvements where the concept was first established (Meier 1984). This approach annualizes the economic impact over the life of the reduction strategy. In order to equitably compare the results in this CEA with other abatement curves, it may be necessary to convert the results to levelized costs using the data already provided.

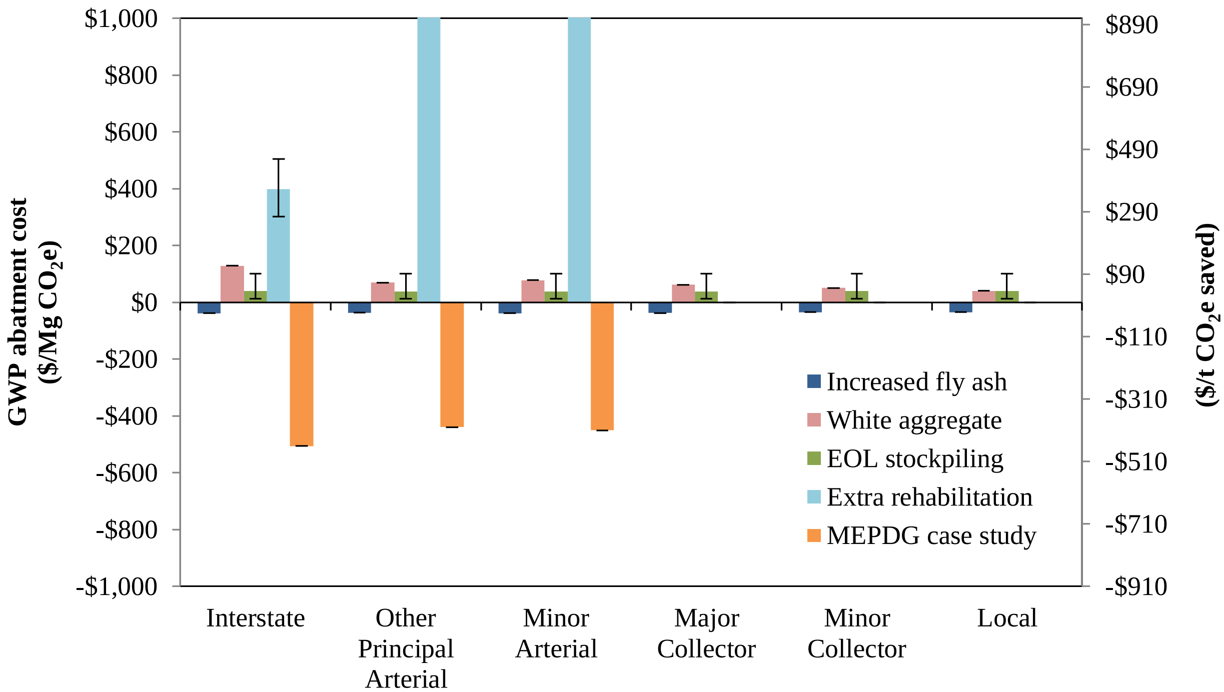

Figure 2.18 – Cost effectiveness of five GHG reduction strategies for rural roadways using discounting (discount rate is 2.3% for solid bars, and 0% and 5% for the min and max range, respectively)

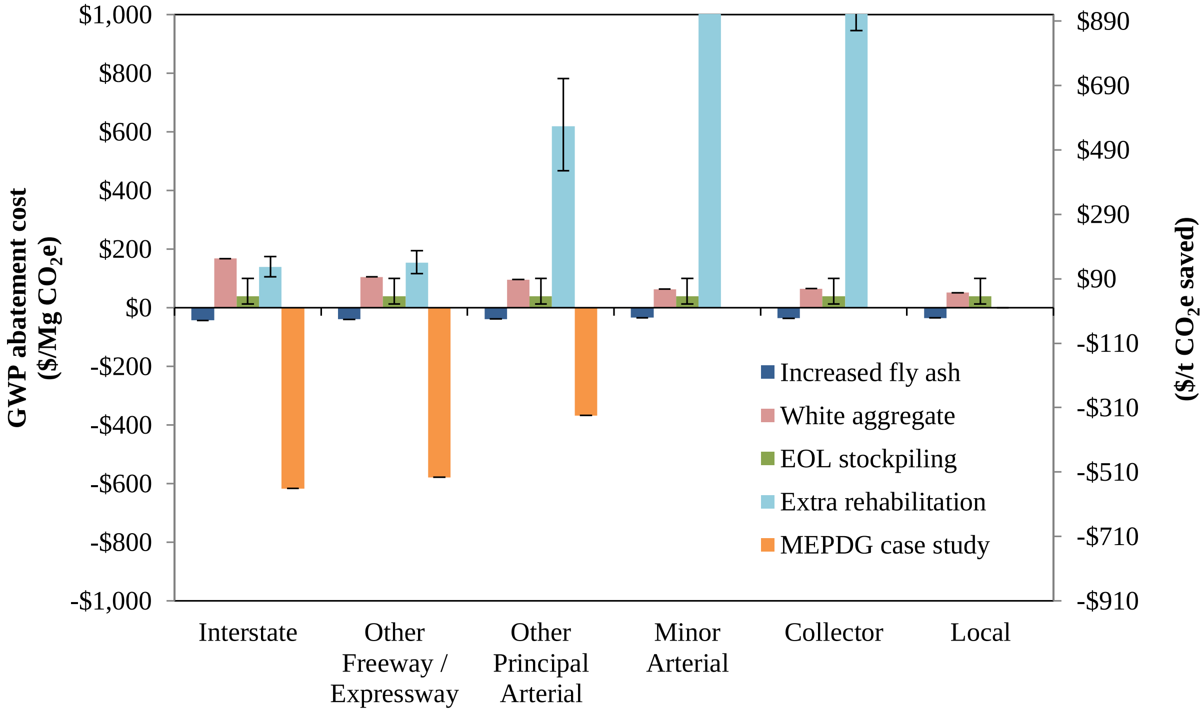

Figure 2.19 – Cost effectiveness of five GHG reduction strategies for urban roadways using discounting (discount rate is 2.3% for solid bars, and 0% and 5% for the min and max range, respectively)

2.8 Discussion

This section includes two primary parts that serve to recapitulate all of Section 2: (1) a summary of the most relevant and interesting key findings that are drawn as conclusions, and (2) a qualitative discussion of the shortcomings of the above approach, as well as recommended future work.

2.8.1 Key Findings

The key contribution of this LCA is the quantification of greenhouse gases embodied in the life cycle of concrete pavements in the United States. This includes a quantification of emissions for current practices, and a measurement of GHG reductions by considering six reduction scenarios. This is done for six urban and six rural roadway classifications, all on a per-kilometer (per-mile) basis over a 40-year analysis period, and on a U.S. network-wide basis for each year, extrapolating 50 years into the future. Emissions are quantified in absolute terms (i.e., X Mg CO_2e per km) and in relative terms (i.e., percent of CO_2e relative to other life-cycle components) so as to accomplish the following: (1) evaluate different roadway classifications; (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 key findings from this section are summarized as follows:

- The life-cycle GWP per kilometer (mile) of new concrete pavement is as follows for the twelve roadway classifications:

Table 2.15 – Summary of life-cycle GWP per km (mi) for new concrete pavements

	GWP (CO_2e)			GWP (CO_2e)	
Rural roadways	Mg/km	t/mi	Urban roadways	Mg/km	t/mi
Interstates	3.8	6.7	Interstates	6.3	11.2
Other principal arterials	1.3	2.3	Other freeways/expressways	4.1	7.3
Minor arterials	1.2	2.1	Other principal arterials	2.4	4.3
Major collectors	0.8	1.4	Minor arterials	1.3	2.3
Minor collectors	0.5	0.9	Collectors	1.0	1.8
Local roads	0.3	0.5	Local roads	0.6	1.1

- The majority of emissions occur during the materials phase, constituting about 65% of the total on urban interstates, 79% on rural interstates, and up to 97% on rural local roads. Cement production has the largest single life-cycle GHG contribution on all roads: from 45% on urban interstates, to 72% on rural local roads.

- 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 GWP per kilometer (mile) can be reduced by approximately 48% on the largest of roads (urban interstates) and by as much as about 70% on the smallest of roads (rural local roads). In Oxnard, CA case study, the MEPDG design procedure leads to pavement designs that have up to 17% reduced GWP.

- The cost of employing the modeled reduction strategies ranges from implausibly high (over \$1,000/Mg CO_2e saved, or \$910/t CO_2e saved) to very cost effective (-\$600/Mg CO_2e saved, or -\$540/t CO_2e saved). Strategies that reduce embodied emissions by reducing natural resource demand (i.e., the fly ash and MEPDG strategies) reduce both costs and emissions for all roadway classifications to which they were applied. Other strategies (white aggregate, EOL stockpiling, and extra rehabilitation) showed promise for certain roadway classifications, but required additional costs for agencies to implement. Project-scale analyses are necessary to determine the cost effectiveness of these strategies under specific conditions.

- The life-cycle GHG emissions for all new concrete pavements constructed in the U.S. is approximately 2.8 Tg CO_2e (3.1×10^6 t CO_2e) per year, or about 0.04% of total emissions in 2009.

2.8.2 Limitations and Future Work

The present LCA 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 report. This allows the study to be reproducible, and allows for the reader to understand the representativeness of the result. 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.

2.8.2.1 Goal and Scope of LCA

Defining the goal of the LCA is an important framing step that enables the research to focus on a clear 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 burden that a product system imposes. The research field will benefit from a similar quantification of other impact categories, such as land use, water consumption, energy consumption, ecotoxicity, human health impacts, natural resource consumption and social impacts. Also, by limiting the present LCA to pavements alone rather than roadway transportation, it removes 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 U.S. economy (EPA 2009).

Additionally, the extrapolation part of this study only considers new concrete construction, without considering reconstruction of existing roadways, because data for this was not available through *FHWA Highway Statistics* or otherwise. This may overlook a large proportion of annual concrete pavement construction. Another important point is that asphalt and composite pavements are also ignored, which represent 74% and 17% of the entire network by lane-kilometers (miles), respectively. While this was not the present focus, it is important not to lose sight that the majority of pavements are asphalt, and many are also composites of asphalt and concrete.

The end of life is modeled using the simplified (and probably conservative) assumption that the concrete is removed after 40 years. Other viable pathways after 40 years could be continued routine maintenance if the concrete was still performing adequately, or more intensive rehabilitation (such as crack and seating or concrete overlays) that takes advantage of remaining structural properties while restoring ride quality. Demolition at year 40 allowed this research to evaluate the end-of-life phase within the scope, but admittedly ignored numerous other realistic options that exist for concrete pavements.

2.8.2.2 Structure Derivation Procedure

The representative structures that are here analyzed incorporate many assumptions in an attempt to derive the “average” structure for each of roadway classification. The need to represent an entire class of roadways using a single average structure is a necessary, but significant, simplification: it inherently ignores the variability that may exist across that classification. For instance, a single value was selected for all structures for the design life, flexural strength, drainage coefficient, and elastic modulus of concrete. A single shoulder and foreslope configuration is assumed for each roadway classification, and 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. 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 are assumed. Admixtures are not accounted for, which include a variety of chemicals that change the material properties of the concrete, including water-reducers, air-entrainers, and others.

2.8.2.3 Life Cycle Assessment Model

There are a simplifications used in the life-cycle modeling procedure and data sources that could be improved upon. For example, AASHTO guidance documents are used to estimate lighting requirements for the GHG reduction scenario, but these recommendations are likely an overestimate of what is actually practiced, especially for rural applications. Another is the influence that pavements have on vehicle fuel consumption, which is a complex interaction that is not fully understood by the science at present (Akbarian 2011). Section 3 of this report provides a first-order model for a particular piece of PVI, but does not provide a comprehensive model for the phenomenon as a whole. For this reason, structural deflection, and the pavement's effect on air temperature and vehicle drag, are not included, but may be significant. The effect of pavement roughness is included because the literature has provided sufficient empirical evidence of the effect, as well as reasonable bounds around its magnitude.

A single carbonation rate was used to estimate baseline emissions, and a single value 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 potential influence that carbonation has on the durability of concrete pavements.

There are limitations to modeling traffic delay using *RealCost*. For example, 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.

2.8.2.4 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. For example, reducing embodied emissions through partial substitution of cement 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, or 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.

Increased albedo is represented using white aggregates in the concrete mix. Other options include using slag or white cements, both of which will provide similar benefits to albedo as using white aggregate, albeit with different life-cycle implications (e.g., high kiln temperatures for white cement, reduced embodied emissions through replacement of cement with slag). Another consideration for the albedo strategy is the reliance on the impact of radiative forcing as the mitigations strategy. 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. Aside from the effects of urban heat island effect and reduced lighting requirements, albedo largely impacts the effective GWP by reflecting more of the sun's radiation out of the earth's atmosphere, not actually mitigating

GHG emissions. 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.

The MEPDG design procedure has been identified as an opportunity for reducing life-cycle GHG emissions by preventing overdesign. Concrete pavement thickness (as determined by AASHTO '93), 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. However, long-term pavement performance data collection programs have shown that concrete pavements can carry more loading than they were designed for (Mack 2010). The analysis presented here is for a specific case study, so the results may or may not be applicable to other locations. A comprehensive 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.

2.8.2.5 Cost effectiveness

The cost effectiveness results represent rough approximations for actual costs that DOTs may incur for mitigating GHG emissions. Actual costs of integrating the modeled GHG reduction strategies are highly variable and uncertain. The sensitivity analyses conducted in Section 2.7 are designed to capture potential cost-effectiveness ranges, but only capture a portion of the possible data and other input permutations that ultimately affect agency costs. While the accuracy could conceivably be increased by collecting better cost data (e.g., through surveys, more representative sources), costs are still highly variable across individual projects. The broad goal and scope of this LCA precludes the use of project-specific data, so imprecision is an expected feature of this CEA. Even with this drawback, quantifying the GHG reduction costs provides decision-makers with a magnitude estimate of the economic implications of reducing GHG emissions.

3 PAVEMENT-VEHICLE INTERACTION: PAVEMENT DEFLECTION*

Pavement-vehicle interaction (PVI) describes the effect of pavement structural and surface properties on vehicle fuel consumption. While the mechanics of PVI are not well understood, previous research has shown that this is a potentially important part of the pavement life cycle, especially for high-traffic roadways (Santero and Horvath 2009). Various empirical studies have looked at the impact of pavement deflection on fuel consumption; however, their main focus has been on a binary material view of asphalt versus concrete pavement, with no consideration of the relationship between pavement deflection and its structure and material (Table 3.1).

Even though the effect of PVI on vehicle fuel consumption is small, its impact within a full pavement life cycle can be significant due to the large number of vehicles that travel over pavements. The change in vehicle fuel consumption between pavement structures due to PVI becomes increasingly important for high volume traffic roadways and can surpass energy consumption and emissions due to construction and maintenance of the roadway system in its lifetime. In general, roughness and deflection of a pavement are considered as the main contributors to pavement vehicle interaction (Santero and Horvath 2009). This section focuses on latter phenomenon: the impact of deflection on PVI and its relation to fuel consumption.

This research uses a mechanistic approach to draw a relationship between pavement structure and material with its deflection, and creates a link between pavement properties and the impact of PVI on fuel consumption. To achieve this goal, this study performs a model calibration and validation for pavement deflection values, estimates fuel consumption caused by the deflection basin, and compares the results to that of existing field data.

3.1 Literature Review

The existing literature has established that a link exists between pavement structure and fuel consumption; for instance, Zaniewski et al. (1982) suggested the extreme example that it would require much more fuel to drive 100 kilometers (62 miles) at the same speed over a gravel road than over a newly paved road. Though less dramatic, measurements (as presented in Table 3.1) have revealed potential fuel consumption differences between flexible and rigid pavements. This change in fuel consumption is attributed to the pavement types tested, albeit overlooking the structural and material properties of each pavement.

A significant hurdle is the measurement precision that is necessary due to the relatively small change in fuel consumption proposed. While the cumulative fuel consumption difference between pavement types can be large when measured over an entire service life, the impact for a single vehicle is quite small; for instance, a study by Taylor and Patten (2006) suggests a maximum fuel consumption difference between flexible and rigid pavements of 0.007 liters per vehicle-kilometer (0.003 gallons per vehicle-mile) for trucks. Measurements at this scale will be highly influenced by external factors including local temperatures (surface, air, tire, etc.), tire pressure, vehicle suspension dynamics, vehicle speed, and other variables. Small shifts in these conditions could affect fuel consumption at the same order as any pavement-type differences; a

* Research conducted with Professor Franz-Josef Ulm

change in tire pressure by 7 kPa (1 psi) can lead to a change in fuel consumption by 0.005 liters per vehicle-kilometer (0.002 gallons per vehicle-mile) (RMA 2010). In order to effectively isolate the effect of pavement type and structure on vehicle fuel consumption, all competing factors must be precisely controlled and accounted for in a given study.

A recent report by the Lawrence Berkeley National Laboratory reviewed the existing literature and determined that although there is strong evidence suggesting a difference between different pavement structures, the aggregate research is often conflicting and inconclusive (Santero et al. 2010). The authors conclude that a comprehensive mechanical model needs to be developed before structure-related PVI is quantitatively included in an LCA.

Table 3.1 summarizes the scope and results from previous studies performed on the impact of pavement type on vehicle fuel consumption. Figure 3.1 graphically presents the values from each study after a critical review and a statistical analysis of their results. This figure shows that a change in fuel consumption due to pavement type exists, however, there is high uncertainty and high variability within the suggested values for the impact of PVI amongst different studies. Studies that suggest there is no change in fuel consumption between the two pavement types or that the change is found to be statistically insignificant are shown in “o”. Since flexible pavements have higher deflection, the fuel consumption on rigid pavements is assumed to be a baseline and the additional fuel consumption on flexible pavements is reported in this figure.

The first study that was performed in this regard observed a fuel consumption increase of 20% for heavy trucks on flexible pavements compared to rigid pavements (Zaniewski et al. 1982); however, their results were statistically insignificant. Since then, more detailed studies have been performed that control for various vehicle parameters and estimate the increase in fuel consumption on flexible pavements to be 0.0–0.7 liters/100km (0.0–0.3 gal/100mi) for a truck and 0.0–0.3 liters/100km (0.0–0.1 gal/100mi) for a passenger car (Taylor and Patten 2006). However, these values depend on vehicle speed, loading, and surface temperature. Recently, two new studies by Yoshimoto et al. (2010) and Lenngren et al. (2011) have also shown fuel savings due to pavement type on concrete pavements. These studies are not included in Table 3.1 and Figure 3.1 as they were not publically available during the literature review process of this study.

Table 3.1 – List of major studies on the effect of pavement type on fuel consumption of vehicles. Increased fuel consumption on an asphalt pavement, compared to a concrete pavement. (SI units, see Table B.1 for U.S. units)

Study	Year	Vehicle Type	Speed (km/hr)	IRI Value (m/km)	Increased Fuel Consumption (liter/100km)	Source
Zaniewski	1982	Trucks	16–110	1–6.7	5.9–8.5	Zaniewski et al. (1982)
Zaniewski	1982	Cars	16–110	1–6.7	-0.7–1.5	Zaniewski et al. (1982)
NRC I	2000	Trucks	100	1–3.5	4.0–4.3	Taylor et al. (2000)
NRC I	2000	Trucks	60	1–3.5	1.6–1.7	Taylor et al. (2000)
NRC II	2002	Trucks	100	1–3.5	1.4–2.3	G.W. Taylor Consulting (2002)
NRC II	2002	Trucks	60	1–3.5	1.4–2.2	G.W. Taylor Consulting (2002)
NPC	2002	Trucks	80	-	0.04–.24	NPC (2002)
De Graaff	1999	Trucks	90	-	-0.2–0.2	De Graaff (1999)
NRC III	2006	Trucks	100	1	0.4–0.7	Taylor et al. (2006)
NRC III	2006	Empty Trucks	100	1	0.2–0.4	Taylor et al. (2006)
NRC III	2006	Full Trucks	60	1	0.4–0.5	Taylor et al. (2006)
NRC III	2006	Cars	100	1	0.2–0.3	Taylor et al. (2006)
U Texas	2009	Cars	60	2.7–5.1	0.4–0.9	Ardakani et al. (2009)
Michigan SU	2010	Trucks	60	-	1	Zaabar et al. (2010)

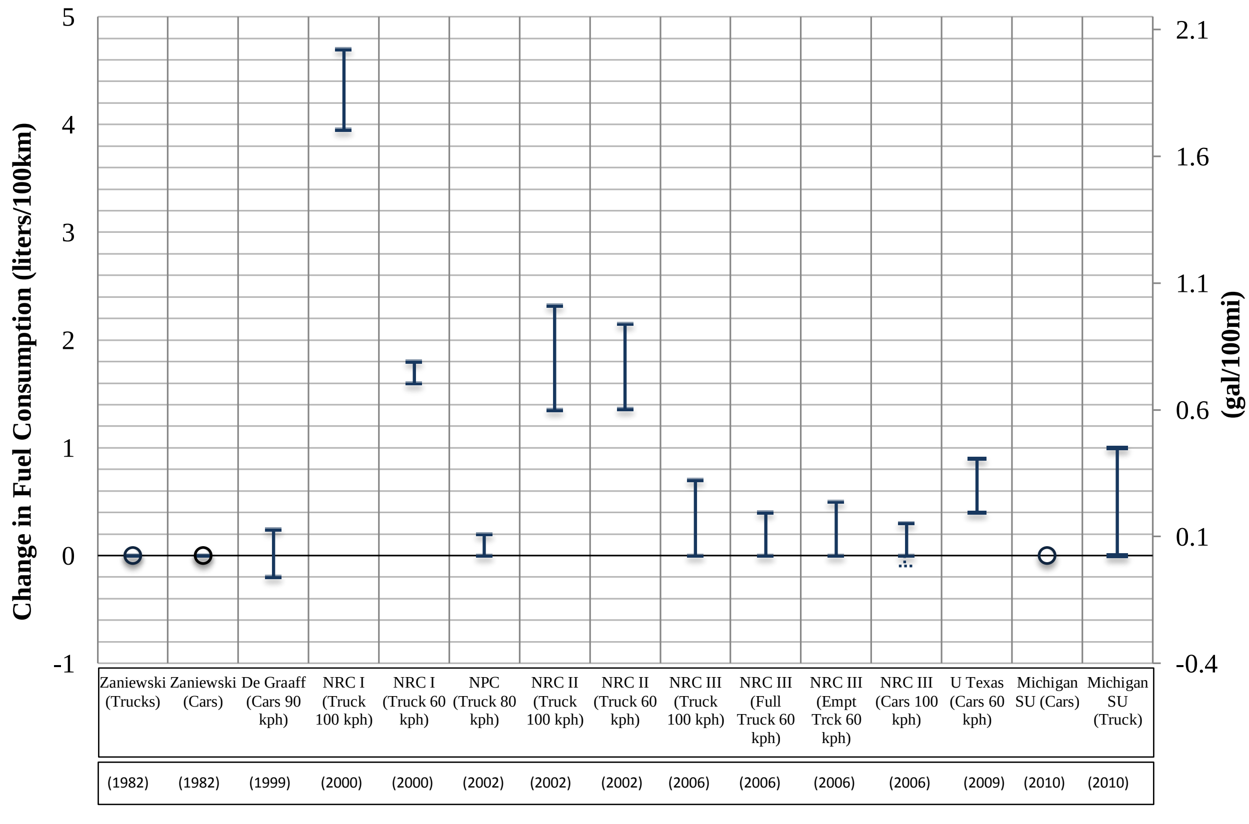

Figure 3.1 – Values reported by previous studies on the effect of pavement type on fuel consumption of vehicles in liters/100km (gal/100mi). Change in fuel consumption on an asphalt pavement compared to a concrete pavement.

3.2 Methodology

In order to understand the impact of deflection on vehicle fuel consumption, there is a need to relate material and structural parameters to deflection of a pavement, and then relate the modeled deflection to change in fuel consumption. This section presents the deflection model and its relationship with fuel consumption.

3.2.1 Model

There are several methods for modeling the dynamic response of a road pavement to moving loads. The pavement can be modeled as a beam, a plate, or the top layer of a multilayer soil system. The substructure can also be modeled as a system of elastic springs with dashpots, or a homogeneous or layered half-space. There are also various methods of modeling the pavement material behavior: elastic, viscoelastic, water-saturated poroelastic or even inelastic. The loads are either presented as concentrated loads, or distributed loads with a finite width. These conditions define the model and the predicted response, under certain material and structural conditions. The pavement deflection response can be calculated through analytical or numerical methods such as the Finite Element Method (FEM), or the Boundary Element Method (BEM). Beskou and Theodorakopoulos (2010) review various models and solution strategies in more detail.

For the purpose of this study, the pavement system is modeled as a beam on damped elastic subgrade with the tire represented as a line load. This model is an idealized representation of the dynamic interaction of pavements and vehicles, but proves to be effective for the purpose of understanding, in first order, the relationship between material and structural elements within PVI and their impact on fuel consumption. Moreover, this model allows for creating scaling relationships between these elements, to better understand their impacts, as presented in Section 3.4.1. The limitations of this assumption with respect to integration in an LCA are discussed in Section 3.4.4.

3.2.1.1 Beam on Damped Elastic Foundation

The deflection response of a beam to a moving load on an elastic, damped, and a viscoelastic subgrade has been extensively studied. This model is coming into attention recently in railway and highway industries, as it is one of the simplest models and it provides a basic understanding of various factors within the structural system (Sun 2001). Figure 3.2 displays a schematic representation of this system.

The beam on an elastic foundation represents various properties of a pavement. It draws a relationship between pavement material properties of top layer elastic modulus E_t, mass per unit length m, and subgrade modulus E_s (referred to as k in the literature), along with the structural property of moment of inertia I, with deflection y under an external load of $q(x,t)$. By assuming a moving coordinate system η on the load (vehicle wheel) a relationship between deflection under (and at distances away from) the load can be calculated. The governing equations of a beam on an elastic foundation are presented in Appendix B.1 in Equations [B.1] to [B.4] in more detail.

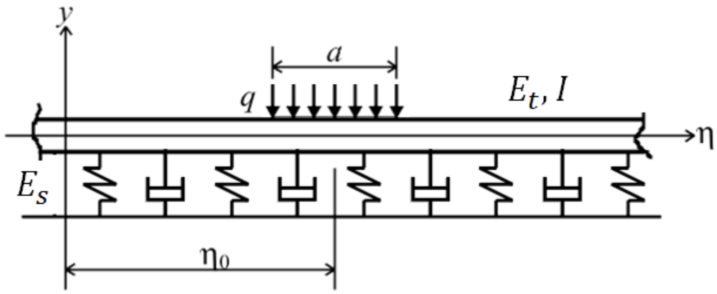

Figure 3.2 – Schematic representation of a beam on damped elastic foundation under line load

3.2.1.2 Solution Strategy

The governing equation of a beam on an elastic foundation can be solved either numerically or analytically (Kim and Roesset 2003; Sun 2001). To solve this equation analytically, the theorem of residue is employed. In this study, a solution strategy similar to that of Sun (2001) is presented in Appendix B.2.

3.2.2 Model output example

Using the solution strategy presented in Appendix B.2, the model response for different input parameters is obtained. Assuming the input parameters suggested by Kim and Roesset (2003), the model response is obtained. Figure 3.3 shows the deflection model response at distances away from the loading zone; distance zero represents the tire location. The model predicted deflection corresponds to results obtained by Kim and Roesset (2003) and Sun (2001).

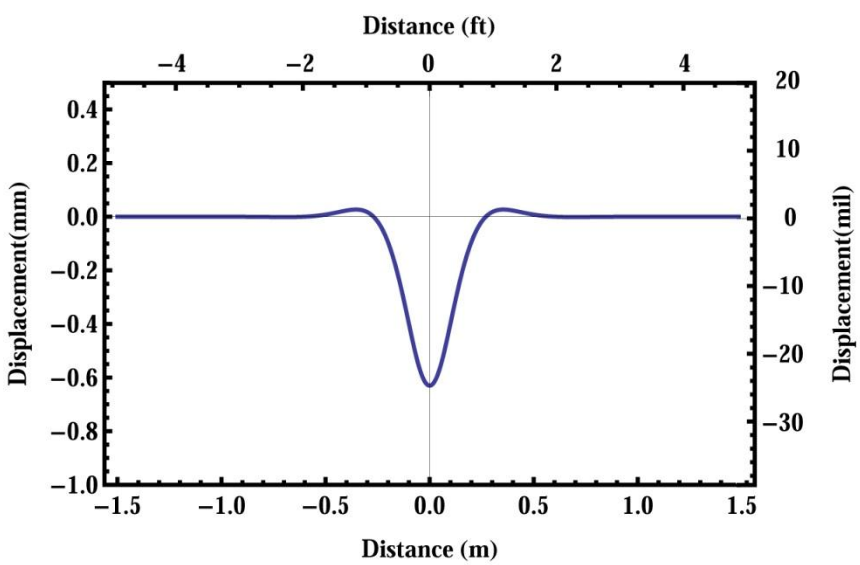

Figure 3.3 – Deflected shape from model response for E_tI=2.3 kN.m^2, E_s=68.9 MPa, *m*=48.2 kg/m, *q*=-70 kN/m, *a*=0.075 m, and *V*=9.525 m/s

3.2.3 Relation to life cycle assessment model

The deflection response of a pavement system and its relationship to pavement structure and material can be linked to change in fuel consumption using empirical studies. There are two classes of studies that can be used to draw such relationship: (1) by treating the deflection as added grade or (2) as added roughness to the pavement surface.

Empirical studies by Park and Rakha (2005), Boriboonsomsin and Bart (2009), and Goodyear (2011) look at the impact of change in road grade on fuel consumption; Zabaar and Chatti (2010) looks at the impact of change in roughness on fuel consumption. In Section 3.4.3, it is shown that using these relations suggests a reasonable change in fuel consumption for the impact of deflection on PVI.

3.3 Results

Calibration and validation of the deflection model is performed against Falling Weight Deflectometer (FWD) time history data recorded by the Long Term Pavement Performance program of the FHWA (LTPP 2011). For the purpose of this study, twelve datasets have been selected, of which nine correspond to asphalt and three correspond to concrete pavements. A normalized load and deflection time history is presented in Figure 3.4. The first line in the graph represents the loading versus time and each of the remaining lines represent deflection at a certain time at various distances (*D* in meters) away from the loading zone. The wave arrival time, measured between the maxima of two deflections, is used for model calibration. The maximum deflection at various distances from the loading point is used for model validation.

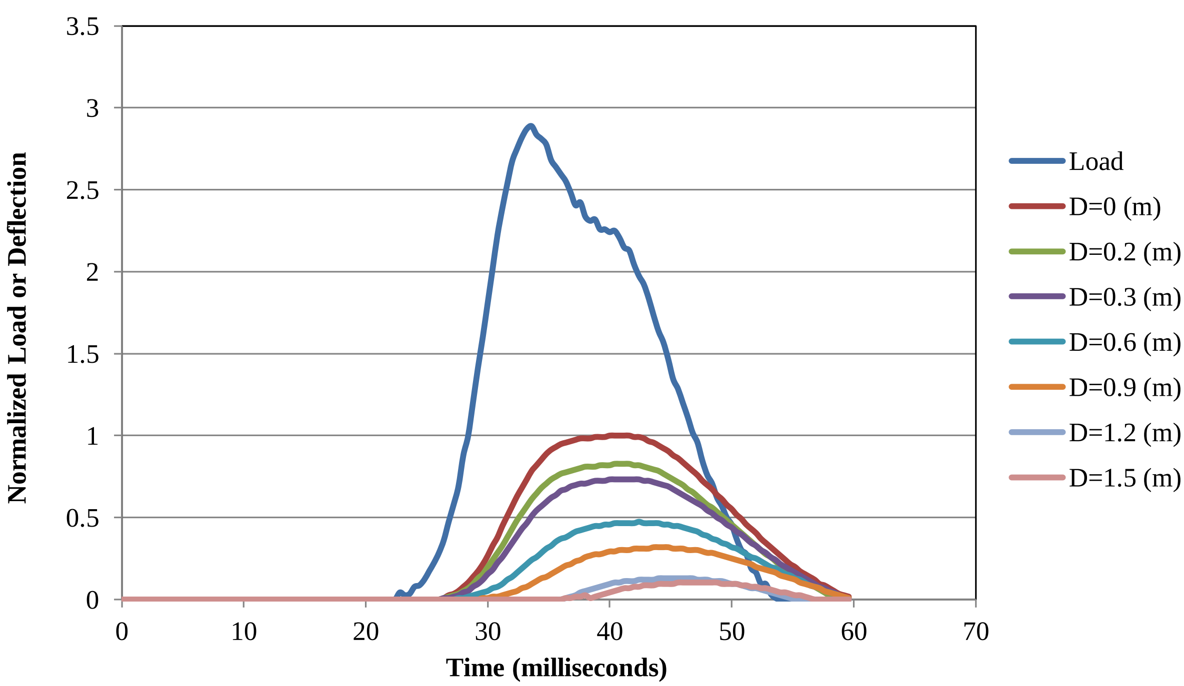

Figure 3.4 – FWD time history obtained from field experiments by the LTPP program of FHWA (LTPP 2011)

3.3.1 Calibration

Considering the arrival time of wave signals at distances away from the loading point (i.e., from Figure 3.4) creates two wave regimes, shown in Figure 3.5. The first wave corresponds to a distance of $D<0.3$ m and travels with higher velocity, hence, it relates to a higher elastic modulus E_t in the top layer. The second wave regime corresponds to $D>0.6$ m, is a lower velocity wave compared to the former, and creates a relationship with the subgrade modulus E_s.

The Rayleigh wave velocity is used to determine the top layer elastic modulus E_t using Equation [3.1], and the P wave velocity can be used to determine the subgrade modulus E_s using Equation [3.2].

For D<0.3 m (Top layer dominated):

[3.1] $$E_t = 2\rho V^2(1+\nu);\ V = \frac{\Delta D}{\Delta T}$$

For D>0.6 m (Subgrade dominated):

[3.2] $$E_s = \rho V^2 \frac{(1+\nu)(1-2\nu)}{(1-\nu)};\ V = \frac{\Delta D}{\Delta T}$$

Values of E_t and E_s, obtained from Equations [3.1] and [3.2] correspond closely to the E_t and E_s values reported by FHWA, and are presented in Table 3.2.

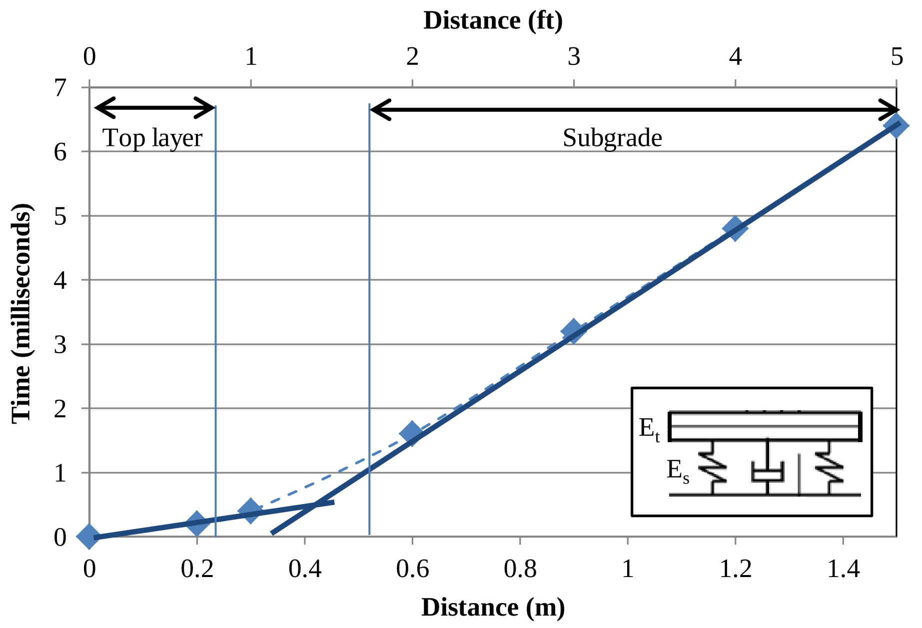

Figure 3.5 – Wave propagation in the upper layer and the subgrade of a pavement along with the signal arrival time at various distances for an asphalt pavement

Table 3.2 – Top layer and subgrade modulus values from calibration and FHWA reported data

		PVI Deflection Model				*FHWA (LTPP 2011)*			
		E_t		E_s		E_t		E_s	
Surface layer		MPa (psi)		MPa	(psi)	MPa (psi)		MPa	(psi)
Asphalt	1	3,715	(5.4×10^5)	66	(9.6×10^3)	4,279	(6.2×10^5)	82	(1.2×10^4)
	2	2,041	(3.0×10^5)	118	(1.7×10^4)	2,358	(3.4×10^5)	97	(1.4×10^4)
	3	3,933	(5.7×10^5)	83	(1.2×10^4)	4,362	(6.3×10^5)	64	(9.3×10^3)
	4	4,721	(6.8×10^5)	120	(1.7×10^4)	5,342	(7.7×10^5)	113	(1.6×10^4)
	5	6,240	(9.1×10^5)	83	(1.2×10^4)	6,845	(9.9×10^5)	87	(1.3×10^4)
	6	6,879	(1.0×10^6)	66	(9.6×10^3)	7,304	(1.1×10^6)	77	(1.1×10^4)
	7	3,895	(5.6×10^5)	83	(1.2×10^4)	4,427	(6.4×10^5)	71	(1.0×10^4)
	8	2,192	(3.2×10^5)	66	(9.6×10^3)	2,568	(3.7×10^5)	73	(1.1×10^4)
	9	3,131	(4.5×10^5)	83	(1.2×10^4)	3,646	(5.3×10^5)	68	(9.9×10^3)
Concrete	1	15,041	(2.2×10^6)	83	(1.2×10^4)	15,489	(2.2×10^6)	94	(1.4×10^4)
	2	18,077	(2.6×10^6)	118	(1.7×10^4)	18,490	(2.7×10^6)	110	(1.6×10^4)
	3	16,035	(2.3×10^6)	120	(1.7×10^4)	16,432	(2.4×10^6)	107	(1.6×10^4)

3.3.2 Validation

After having calibrated the model to determine top layer and subgrade moduli, validation of the deflection model is carried out against deflection values from the FWD tests at various distances away from the loading point. Figure 3.6 shows the FWD experimental deflection values versus the model predicted deflection values for the damped and un-damped cases assuming a 20 cm (8 in) thick top layer and a 1 m (3.3 ft) unit width. Damping is used as a free parameter to create a better model prediction of deflection values. It is observed that the experimental deflection and predicted values from the model highly correspond for the damped and undamped cases, but are refined in the case of the damped subgrade. Figure 3.7 represents an asphalt and a concrete pavement's deflection basin as predicted by the model and from FWD test experiments. It is observed that the model predictions match the experimental deflection to an acceptable accuracy due to the high R^2 values for both the damped and undamped cases.

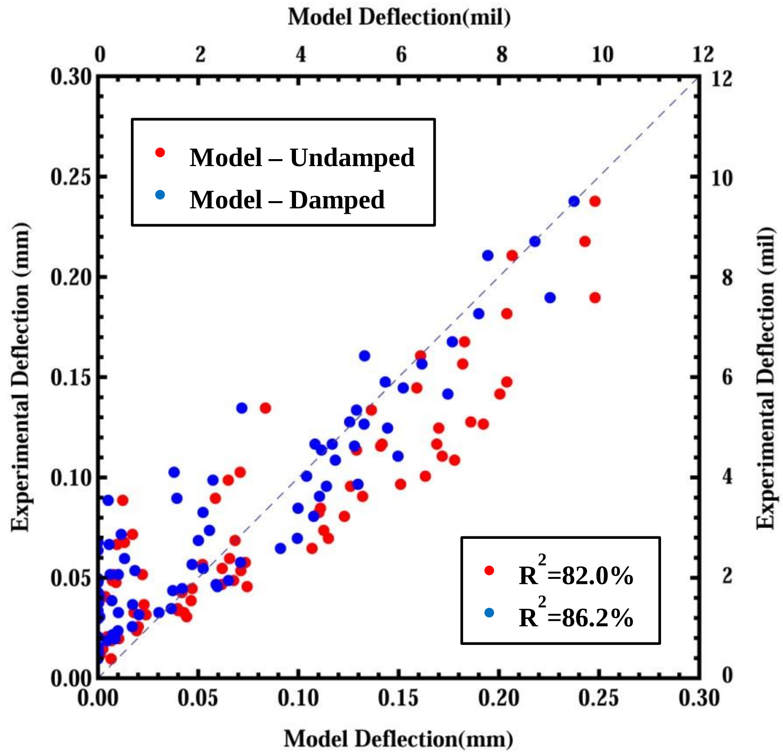

Figure 3.6 – Model validation: observed experimental vs. model predicted deflection values for twelve pavement cases

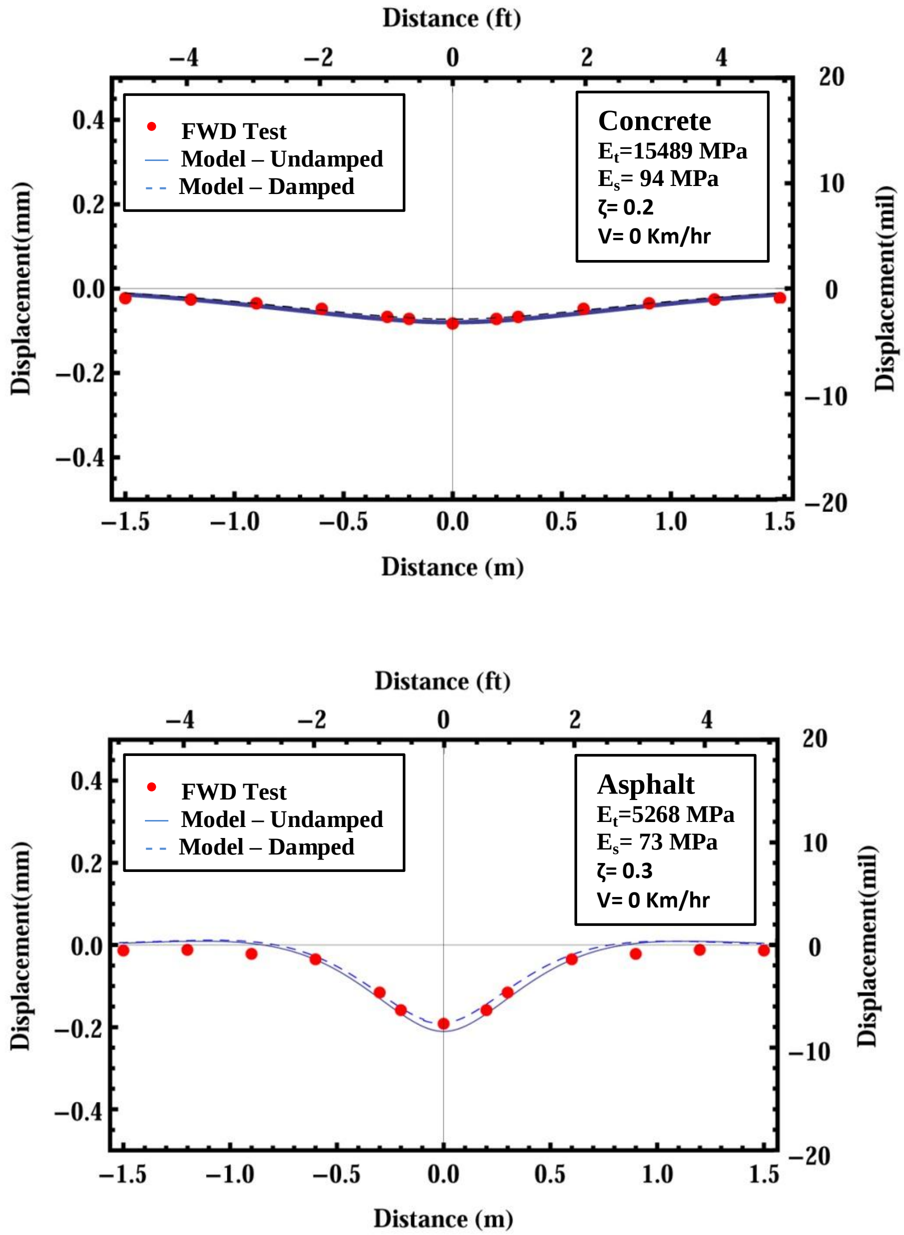

Figure 3.7 – FWD test vs. model prediction of the deflection basin for a concrete (top) and an asphalt (bottom) pavement

3.4 Discussion

After the model has been calibrated and validated, it is necessary to obtain the importance of different parameters that affect fuel consumption due to the deflection of a pavement. To achieve this goal, two scaling discussions are presented in this section, followed by a comparison of model predicted values and those from empirical field measurements. These values are then discussed regarding their implementation into pavement LCAs.

3.4.1 Scaling

As stated earlier, the beam on damped elastic foundation is an idealized model and allows first-order understanding of the importance of different input parameters and their impact on pavement deflection. The main input parameters that correspond to the pavement structure and material, along with its response to an outside load are:

- M: Loading weight
- E_t: Top layer elastic modulus
- E_s: Subgrade modulus
- h: Top layer thickness

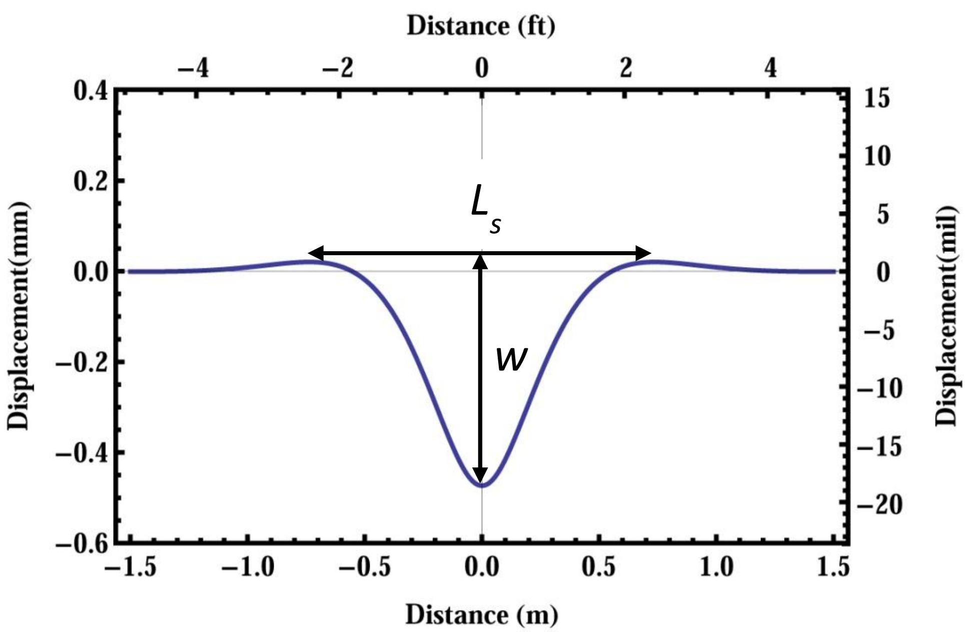

Figure 3.8 – Representation of deflection and characteristic wavelength

It can be observed from the equations of beam on damped foundation and from the model, that deflection w, and characteristic wavelength L_s as shown in Figure 3.8, have the following relations with the above parameters:

[3.3] $$w \sim M^1 \, E_t^{-1/4} \, E_s^{-3/4} \, h^{-3/4}$$

[3.4] $$L_s \sim E_t^{1/4} \, E_s^{-1/4} \, h^{3/4}$$

GR is defined as the change in the pavement's grade, and is represented as:

[3.5] $$GR \sim \frac{w}{L_s}$$

plugging in w and L_s into Equation [3.5] gives:

[3.6] $$GR \sim M \times E_t^{-1/2} \, E_s^{-1/2} \, h^{-3/2}$$

This scaling relationship shows the importance of the loading M, along with that of material parameters E_t and E_s, and structural component h. It is shown that the pavement thickness h is of higher importance compared to the other parameters in reduction of the impact of deflection within PVI.

3.4.2 Scaling of Fuel Consumption

The fuel consumption of a vehicle is in a direct relationship with the resisting forces that it has to overcome to travel on a pavement. By defining the gradient force in Equation [3.7], a link can be established between the instantaneous fuel consumption (IFC) (Equation [3.8]) and the pavement properties as shown in Equation [3.9].

[3.7] $$\text{Gradient Force} = GR \times M \times \mathrm{g}$$

[3.8] $$IFC \sim GR \times M \times \mathrm{g}$$

[3.9] $$IFC \sim M^2 \times E_t^{-1/2} \, E_s^{-1/2} \, h^{-3/2}$$

where g is the acceleration of gravity.

To illustrate the importance of such a scaling relationship, various examples can be represented. For example, if two pavements are assumed with the same subgrade modulus, and under the same load with moduli of elasticity of $E_{t1} = 5{,}000\ MPa$ and $E_{t2} = 20{,}000\ MPa$, and the same IFC is pursued, equation [3.9] can be used to determine thickness ratios of the two pavements:

[3.10] $$\frac{IFC_1}{IFC_2} = \frac{M^2 \times E_{t1}^{-1/2} \, E_s^{-1/2} \, h_1^{-3/2}}{M^2 \times E_{t2}^{-1/2} \, E_s^{-1/2} \, h_2^{-3/2}} = 1$$

[3.11] $$\frac{h_1}{h_2} = \sqrt[3]{\frac{E_{t2}}{E_{t1}}} = \sqrt[3]{\frac{20{,}000}{5{,}000}} = 1.6$$

Equation [3.11] shows that Pavement 1 would have to be 1.6 times thicker than Pavement 2 to maintain the same instantaneous fuel consumption caused by deflection of the pavement under the gradient force.

3.4.3 Comparison with Field Data

As stated earlier, the added fuel consumption due to pavement deflection can be modeled as added grade or added roughness to the roadway. The studies by Park and Rakha (2005), Boriboonsomsin and Bart (2009), Goodyear (2011), and Zabaar and Chatti (2010) differentiate between different vehicle classes and the impact of each on the fuel consumption; hence, impacts of PVI on passenger vehicles and trucks are considered in this section. The assumed weights of both vehicle classes are drawn from their corresponding studies. Tables 3.3 and 3.4 present the change in fuel consumption due to deflection of the pavement modeled as added grade and as added roughness respectively. It should be noted that the values suggested here are drawn from the twelve FWD test data obtained from FHWA, and are not representative of all asphalt and concrete pavements; only those studied here and shown in Table 3.2.

Table 3.3 – Impact of deflection on fuel consumption modeled as added grade to the roadway assuming a 200 mm (8 in) pavement, for pavements described in Table 3.2

	Change in fuel consumption in liters/100km (gal/100mi)			
	Concrete		Asphalt	
Vehicle type	Min	Max	Min	Max
Passenger	0.0034 (0.0014)	0.005 (0.002)	0.0068 (0.003)	0.08 (0.03)
Truck	0.02 (0.008)	0.023 (0.01)	0.033 (0.014)	0.14 (0.06)

Table 3.4 – Impact of deflection on fuel consumption modeled as added roughness to the roadway assuming a 200 mm (8 in) pavement, for pavements described in Table 3.2

	Change in fuel consumption in liters/100km (gal/100mi)			
	Concrete		Asphalt	
Vehicle type	Min	Max	Min	Max
Passenger	0.0058 (0.002)	0.0064 (0.003)	0.008 (0.003)	0.11 (0.046)
Truck	0.031 (0.013)	0.043 (0.02)	0.08 (0.03)	0.26 (0.11)

In these tables, the Min and Max values represent pavements with the maximum and minimum deflections respectively. The influence of vehicle weight is clearly represented, with trucks having significantly larger differences in fuel consumption. Comparing Table 3.3 with Table 3.4, it is evident that modeling the impact of PVI on fuel consumption as added grade or roughness produces results of the same order of magnitude.

Comparison of these values to previously performed empirical studies (Figure 3.1) shows that the model suggests changes in fuel consumption due to PVI on the same order of magnitude as suggested by some of the more recent studies. Aside from having related the impact of pavement deflection on fuel consumption with regards to pavement structure and material, this model uses a completely flat pavement with no deflection as a benchmark, which results in a meaningful comparative approach for use in a pavement LCA.

3.4.4 Use in LCA

In the previous section, a comparison of model predictions and empirical field data showed that the model is not only suggesting comparable values for change in fuel consumption, but it is also creating a connection between the impact of pavement vehicle interaction and the material and structures involved. However, as mentioned earlier, this study presents a simplified model that rationalizes PVI in first order and does not capture all phenomena involved within it. For instance, this model assumes that both asphalt and concrete pavements are continuous (i.e., no joints). Moreover, the impacts of aging of the pavement such as cracking, rutting, faulting etc. are not taken into account. It is important to note however, that the changes in fuel consumptions suggested by the model are conservative both for concrete and asphalt, and impacts of aforementioned phenomena will increase fuel consumption.

In order to emphasize the importance of such small changes in fuel consumption, two partial LCA scenarios are presented in this section. The pavement designs, traffic scenarios, and the lifetime of the pavement, along with GHG emissions involved with production, maintenance, and rehabilitation of asphalt and concrete pavements are extracted from Athena (2006). The Athena report on the GWP and energy consumption of asphalt and concrete pavements presents their assumptions with high transparency. However, the authors of the Athena report did not consider the impacts of PVI within their results, and it is shown here that consideration of this phenomenon would have a significant influence on the results.

The scenarios used from Athena (2006) are the values for the Canadian High Volume Highway and that of the Canadian Arterial Highway constructed on a subgrade foundation support having a California Bearing Ratio (CBR) of 3. Traffic volumes for the roadways are 50,000 and 15,000 AADT, respectively, both with 10% truck traffic. The functional units for both scenarios are two lane-kilometers with 50 year analysis periods. To produce impacts of PVI and changes in fuel consumption, minimum, average, and maximum values from Tables 3.3 and 3.4 are used.

Figure 3.9 presents the values from Athena (2006) for both high volume and arterial roadways in blue, and the average value for the impact of PVI (aggregated of trucks and cars) in red for asphalt and concrete pavements; the maximum and minimum ranges in impacts of PVI are shown with the error bars, reflecting the range of stiffness values currently modeled for each pavement type. It is clear that the impact of PVI is more significant for the high-volume freeway than for the low-volume arterial. Using the average values for the impact of PVI, it is seen that PVI-related emissions go as high as that of embodied emissions in the case of the high volume asphalt pavement. It is necessary to note that the AADT on the high-volume roadway is assumed at 50,000 AADT for two-way traffic with two lanes in each direction; this traffic volume corresponds with values suggested in section 13.2.1 of highway statistics (FHWA 2008) for daily average vehicle per lane on urban interstates with an AADT of 13,355 per lane. On highways with higher congestion values (AADT per lane) the impact of PVI would be even more magnified.

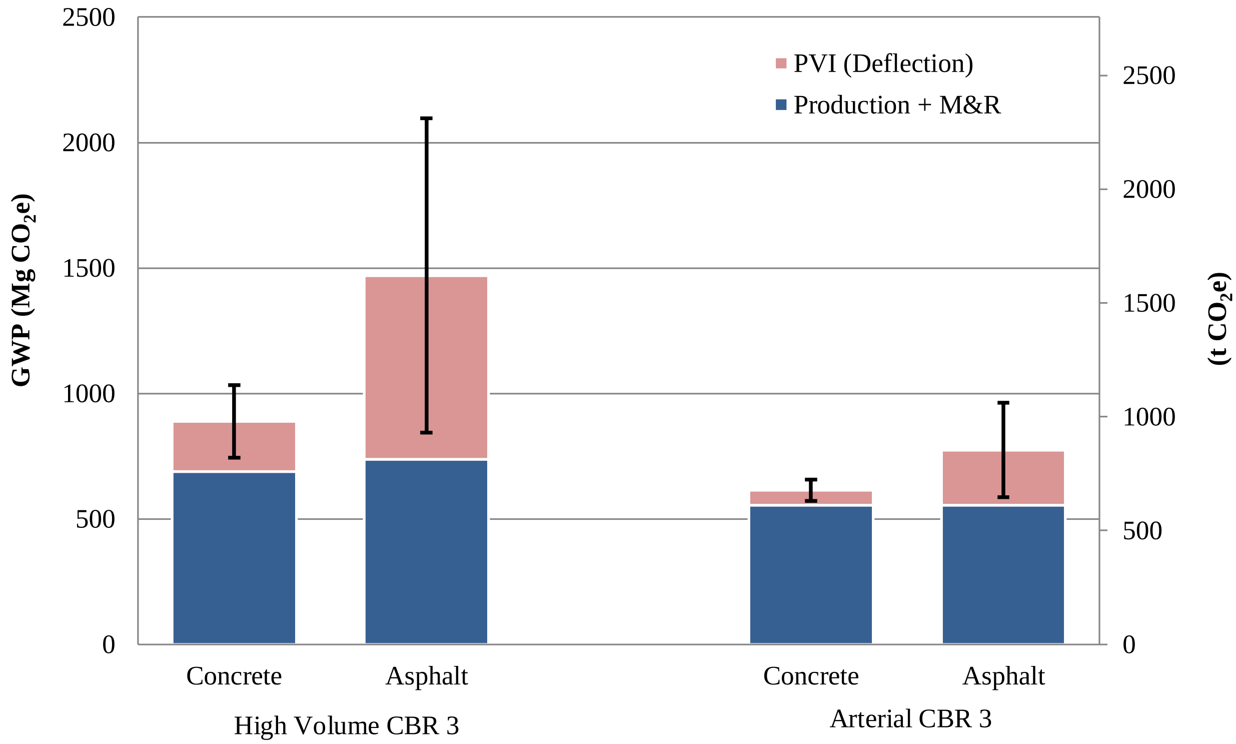

Figure 3.9 – Use of model predicted values in an LCA. Production and M&R values are extracted from Athena (2006)

3.4.5 Limitations and Future Work

The goal of this work has been to create a first-order understanding of the impact of deflection within pavement-vehicle interaction and the effect of structural and material properties on fuel consumption. Even though more accurate models and solution strategies for calculation of pavement deflection exist, a beam on an elastic damped foundation is used to create scaling relationships between structural and material properties of the pavement with changes in fuel consumption. This solution strategy proved to be sufficiently accurate for calculation of the change in fuel consumption and its order of magnitude.

In order to create a more refined understanding of the impact of pavement deflection on fuel consumption, more components need to be added to the model to represent discontinuities, aging, temperature effects, and other phenomena that can affect the pavement response. Moreover, the combined effects of roughness and unevenness of the pavement with deflection need to be accounted for in order to capture pavement-vehicle interaction and all its components within the model.

Lastly, the new modeling approach to PVI defines a baseline for fuel consumption of pavement structures in function of the relevant material and geometrical design parameters. The accuracy of the model relates to the mechanical model assumptions, such as straight pavement, neglecting of joints, aging, and other factors, thus warranting further validation through extensive field measurements, particular for pavements designed according to MEPDG.

3.5 Conclusion

This study presents a first-order mechanistic model that rationalizes the impact of deflection within the pavement-vehicle interaction. The model has been calibrated and validated against twelve falling weight deflectometer time histories, previously performed by the FHWA's LTPP program. This data has been used to develop a relationship between vehicle mass, layer stiffness, layer thickness and vehicle fuel consumption. This relationship provides realistic estimates of change in fuel consumption due to deflection when compared to previously-performed empirical studies.

It was shown that the scaling of input parameters is critical, as it provides a quantitative link between pavement design and its impact on PVI in an LCA. Such relationships demonstrate the level of importance of each parameter on the final impact within an LCA, and can guide pavement design for reduction of PVI related emissions.

The model provides a first-order estimate of the importance of various factors that affect fuel consumption, and hence, an LCA. The impact of pavement deflection on fuel consumption is magnified within an LCA of a high-volume roadway, and can exceed the impacts from the materials, construction, and maintenance phases of the pavement life cycle. As such a model matures to include more aspects of PVI, it can be implemented into design procedures and tools such as MEPDG.

4 DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

This research develops a comprehensive pavement life cycle assessment methodology and model to quantify the greenhouse gas (GHG) emissions of pavements. The methodology is applied to evaluate the concrete pavement life cycle by quantifying current emissions, identifying opportunities for improvements, and calculating the cost effectiveness of emissions reduction strategies. Finally, to improve the supporting science for pavement LCAs, the impact of pavement structure and material properties on pavement-vehicle interaction is investigated. This section reviews of the key findings and contributions and provides guidance as to where future research can build upon the work presented here.

4.1 Summary of Findings and Contributions

This research has advanced the field of life cycle assessment of concrete pavements in three key areas: (1) methodology, (2) quantification, and (3) pavement-vehicle interaction. These advancements provide the pavement community with new knowledge and methods that can be used to reduce the impacts of the pavement infrastructure. The following summarizes the contributions that are made with respect to each of the objectives presented in Section 1.1.

Methodological advancements improve the ability of future pavement LCAs to produce accurate and comprehensive results. They also contribute to the pavement LCA standardization process by putting forth good-practice concepts and processes. Specific contributions to the general methodology include the following:

- Identifies and describes key transparency requirements for conducting pavement LCAs and LCCAs (Table 1.1), and transparently documents key parameters for reproducibility of results (Table 2.1 through 2.5, Table 2.12, and tables in Appendix A).
- Establishes comprehensive system boundaries that include each phase and component of the pavement life cycle (Figure 2.1), as well as a systematic approach for evaluating life-cycle variability across different roadway classifications.
- Applies the methodology to a specific project (Section 2) in order to demonstrate the execution of a good-practice concrete pavement LCA.

The concrete pavement LCA conducted in Section 2 quantifies current performance and identifies GHG reduction opportunities for concrete pavements. Specific contributions from the LCA include the following:

- Quantifies life-cycle GHG emissions per km (mi) for concrete pavements for a range of FHWA roadway classifications (Figure 2.2).
- Demonstrates the largest GHG contributions by life-cycle component (Figure 2.3), the time series of emissions (Figures 2.4 and 2.5), and the sensitivity of the results to the various input parameters (Figures 2.10 and 2.11). Cement production is the largest single CO_2e contributor for each structure considered, although vehicle fuel consumption related to pavement roughness is nearly as large for high-volume roadways.

- Estimates a national, network-level extrapolation for GHG emissions due to the construction of new concrete pavements each year (Figure 2.6), resulting in a rough estimate of 0.04% of total U.S. annual emissions.

- Evaluates a demonstrative set of GHG emission reduction strategies that evaluated four different reduction pathways: reducing embodied emissions, increasing albedo, increasing carbonation, and reducing vehicle fuel consumption (Figures 2.12 through 2.15). When multiple strategies are applied over the life cycle, large GHG reductions (37–70%) are possible.

- Evaluates cost effectiveness of emissions reduction strategies by combining LCCA and LCA, providing results in terms of \$/Mg CO_2e saved (Figures 2.16 through 2.19). Strategies for reducing embodied emissions (increasing fly ash content and avoiding overdesign by using MEPDG) reduced both costs and emissions. Other strategies reduce emissions at the expense of increased costs, although costs in some scenarios are comparable to the current price of carbon.

To fill in existing knowledge gaps, the supporting science is improved through the development of a mechanistic model describing the role of pavement deflection on fuel consumption, in order to evaluate this effect during the pavement life cycle. Significant contributions to PVI include the following:

- Develops and calibrates a first-order mechanistic model relating pavement structure and material properties to pavement deflection, and pavement deflection to vehicle fuel consumption.

- Validates the model with respect to FWD deflection data from FHWA LTPP empirical studies, and generates results comparable to prior studies examining fuel consumption due to pavement structure.

- Estimates the potential impact that fuel consumption could have in pavement LCA studies and provides a framework for guiding pavement design in order to reduce PVI-related emissions.

4.2 Future Research

The methodology, quantitative analyses, and novel mechanistic model introduced in this research provide insight into the impacts of a complex and pervasive infrastructure system. Future research can build upon the foundation established here by broadening the scope, expanding the application, and improving upon the presented models.

Development of a standardized, widely-accepted pavement LCA framework is essential in order to increase the accuracy and consistency of future analyses. The general methodology concepts presented in Section 1, together with the detailed LCA presented in Section 2, put forth a good-practice approach that can provide insight during the standardization process. Although the application is focused on concrete pavements, the underlying principles apply to all pavement types and analysis scopes. Moving forward, involvement of all relevant stakeholders (e.g., industry organizations, government agencies, academic institutions) is necessary in order to develop a single comprehensive framework that allows for accurate and consistent assessments, including comparisons across different pavement types. The scope could also be broadened to include the impacts of the decision to build a roadway, such that pavement infrastructure could be reliably compared to other forms of transportation infrastructure. This is especially true when considering new construction, since network expansion can induce increased vehicle production and vehicle traffic, potentially trumping the impact of the pavement alone.

The focus on new concrete pavements enabled this research to evaluate and provide recommendations for a specific pavement type. However, concrete pavements represent less than 10% of all lane-kilometers (lane-miles) over the U.S. pavement network, with the rest having asphalt or composite structures (FHWA 2008). Additionally, new concrete pavement construction only represents a portion of all concrete construction, and ignores the potentially large activities from rehabilitation and reconstruction, for which no FHWA data was available. In order to provide comprehensive LCA-based strategies for reducing network-level GHG emissions, research should be performed that complements the results and conclusions presented here. Quantifying emissions and evaluating improvement strategies for asphalt and composite structures, and pavement reconstruction, will allow transportation agencies to develop holistic approaches to increasing the sustainability of their transportation infrastructure.

There are drawbacks associated with the simplifying assumptions involved with doing an LCA of any complex product system, and these are especially true when it is generalized to a product that extends across an entire country. Condensing the entire U.S. concrete pavement network down to twelve representative types, as well as estimating each life-cycle component based on limited data, inevitably involves errors that are difficult to ascertain in a rigorous fashion. Uncertainty analysis in LCA is a growing field, and there is potential future work to apply it to pavements. Additionally, while the focus on GHG emissions is an important environmental metric to evaluate, sustainable policies should consider multiple impact categories. Natural resource consumption, energy consumption, human health damage, and other types of burdens are important to address with regards to environmental impact. Future research that includes other pavement structural materials and impact categories will provide decision-makers with a more complete understanding of how to improve sustainability.

The reduction strategies for concrete pavements presented in Section 2 are only a demonstrative set of opportunities for improvement within the pavement life cycle. The broader reduction categories considered—reducing embodied emissions, increasing albedo, increasing carbonation, and improving PVI—represent general approaches that can be used to reduce GHG emissions. For example, embodied emissions can be reduced through more efficient cement manufacturing processes, mix design optimization techniques, or cement substitution using SCMs other than fly ash (which was modeled in this research). Similarly, alternative strategies can be identified for other reduction categories, or even entirely new categories for emission reductions can be identified. This research quantified and costed a few select strategies, with the intent that future research will be able to build upon methods in order to develop a more exhaustive set of reduction strategies.

Finally, the work PVI model presented in Section 3 represents a significant step towards quantifying an important component in the pavement life cycle. The mechanical relationship provides a first-order method to quantify how material and structural properties of pavements affect fuel consumption. This simplified model rationalizes PVI, but does not capture impacts of discontinuities, cracking, rutting, faulting, and other factors on vehicle fuel consumption. The model is conservative in case of both asphalt and concrete pavements, and suggests values for fuel consumption that would increase with addition of such phenomena. As the model develops, such factors need to be added to bring the analysis closer to complete.

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APPENDIX A. SUPPORTING INFORMATION FOR SECTION 2

Table A.1 – Assumptions for structure designs for AASHTO design procedure

	Rural Roads						Urban Roads					
Roadway classification	Interstate	Other Prin. Arterial	Minor Arterial	Major Collector	Minor Collector	Local Road	Interstate	Other Fwy / Expy	Other Prin. Arterial	Minor Arterial	Collector	Local Road
"Estimated lane-miles by functional system" from Table HM-60 (FHWA 2008)												
2008	122,825	249,998	280,608	840,864	525,215	4,072,433	90,763	52,780	227,520	272,077	242,715	1,506,1 71
"Length by functional system" (miles) from Table HM-20												
2008	30,196	94,949	135,024	418,229	262,607	2,036,217	16,555	11,335	64,557	106,172	113,848	753,089
"Vehicle miles of travel, by functional system" (MILLIONS) From Table VM-202 (FHWA 2008)												
2008	243,290	222,298	151,975	186,139	55,019	131,697	476,091	222,624	462,569	377,033	175,389	269,385
Lanes (Mean)	4.1	2.6	2.1	2.0	2.0	2.0	5.5	4.7	3.5	2.6	2.1	2.0
Inner Shoulders	2.0	0.0	0.0	0.0	0.0	0.0	2.0	2.0	0.0	0.0	0.0	0.0
Outer Shoulders	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Lanes (Mode)	4.0	2.0	2.0	2.0	2.0	2.0	6.0	4.0	4.0	2.0	2.0	2.0
AADT	22074	6414	3084	1219	574	177	78789	53809	19631	9729	4221	980
Low End AADT	7324	1711	782	190	144	18	29374	16604	10348	2944	965	578
High End AADT	35092	10879	7150	3471	1005	337	132935	92097	32751	17572	7972	1382
AADTT	4314	670	322	96	45	14	6678	2542	927	460	199	46
Low End AADTT	1431	179	82	15	11	1	2489	784	489	139	46	27
High End AADTT	6857	1136	746	273	79	26	11267	4351	1547	830	377	65
Single Unit only (%)	0.03	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Combination only (%)	0.17	0.07	0.07	0.05	0.05	0.05	0.06	0.02	0.02	0.02	0.02	0.02
Direction Distibution	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Lane Distribution	0.9	1	1	1	1	0.9	0.8	0.9	0.9	1	1	1
Service Life	20	20	20	20	20	20	20	20	20	20	20	20
Daily Rigid ESALs[1]	23,947,182	4,130,492	1,985,719	591,036	278,226	77,301	32,952,642	14,113,208	5,148,829	2,835,320	1,230,013	285,601
Low End ESALs	7,945,709	1,101,856	503,566	91,853	69,556	7,730	12,285,164	4,354,822	2,714,171	857,807	281,283	168,362
High End ESALs	38,069,797	7,005,489	4,604,214	1,682,436	486,895	146,872	55,598,319	24,155,366	8,589,886	5,120,906	2,323,234	402,840
Reliability =	95%	90%	80%	80%	75%	75%	95%	95%	90%	80%	75%	75%
Zr =	-1.64	-1.28	-0.84	-0.84	-0.67	-0.67	-1.64	-1.64	-1.28	-0.84	-0.67	-0.67
So =	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Flex Strength S'c =	650	650	650	650	650	650	650	650	650	650	650	650
Cd =	1	1	1	1	1	1	1	1	1	1	1	1
J = (dowels w/ J=2.8, No	2.8	2.8	3.2	3.2	3.2	3.2	2.8	2.8	2.8	2.8	3.2	3.2
J (Low End)	2.8	3.2	3.2	3.2	3.2	3.2	2.8	2.8	2.8	2.8	3.2	3.2
J (High End)	2.8	2.8	2.8	3.2	3.2	3.2	2.8	2.8	2.8	2.8	3.2	3.2
Ec =	4,200,000	4,200,000	4,200,000	4,200,000	4,200,000	4,200,00	4,200,000	4,200,000	4,200,000	4,200,00	4,200,000	4,200,0
PSIi =	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
PSIt (72 and 86)=	2.75	2.5	2.5	2.5	2.5	2.5	2.75	2.75	2.5	2.5	2.5	2.5
k (granular base) =	150	150	150	150	100	100	150	150	150	150	100	100
D (inches)	11.5	8.1	7.3	5.8	5.1	4.0	12.0	10.6	8.4	7.1	6.7	5.1
D Low End	9.7	7.0	5.6	4.0	4.0	4.0	10.3	8.8	7.5	6.2	5.1	4.6
D High End	12.3	8.8	7.8	7.0	5.6	4.5	13.0	11.5	9.1	7.9	7.5	5.4

[1] Traffic growth rate is negligible, based on 0.8% growth from 1999-2008 (FHWA 2008)

Table A.2 – *RealCost* outputs and subsequent calculations

Normal Conditions	Rural Network Interstate	Other Principal Arterial	Minor Arterial	Major Collector	Minor Collector	Local Road	Urban Network Interstate	Other Freeway /Expressway	Other Principal Arterial	Minor Arterial	Collector	Local Road
AADT (veh/day)	22,074	6,414	3,084	1,219	574	177	78,789	53,809	19,631	9,729	4,221	980
Cars as % of AADT	80	90	90	92	92	92	92	95	95	95	95	95
AADTT-SU (%)	3	4	3	2	2	2	2	2	2	2	2	2
AADTT-Comb (%)	17	7	7	5	5	5	6	2	2	2	2	2
Traf Growth Rate %	1.15	0.28	0.33	0.54	0.54	0.85	1.15	1.15	0.28	0.33	0.54	0.85
Normal Spd(mph)	65	55	45	30	30	30	65	65	55	45	30	15
Lanes	4	2	2	2	2	2	6	4	4	2	2	2
FreeFlow Cap. (vphpl)	2298	1699	1699	1699	1699	1699	2299	2299	2299	1700	1700	1700
Rural/Urban Capacity	Rural	Rural	Rural	Rural	Rural	Rural	Urban	Urban	Urban	Urban	Urban	Urban
Q Dsp Cap (vphpl)	1798	1799	1799	1799	1799	1799	1799	1800	1800	1800	1800	1800
AADTmax (veh/day)	227,777	85,955	85,955	85,966	85,966	85,966	341,855	227,946	227,946	85,980	85,980	85,980
Max Q Length (mi)	n/a	n/a	n/a	n/a	n/a	n/a	1.34	5	n/a	n/a	n/a	n/a
10-hr closure	PRODUCTIVITY RATE = 0.09											
Initial Construction												
Work Zone Duration	27.1	13.6	13.6	13.6	13.6	13.6	40.7	27.1	27.1	13.6	13.6	13.6
# Lanes Open in Each Dir During Work	1	0.5	0.5	0.5	0.5	0.5	2	1	1	0.5	0.5	0.5
Activity Service Life	20	20	20	20	20	20	20	20	20	20	20	20
Maintenance Freq	20	20	20	20	20	20	20	20	20	20	20	20
Work Zone Length	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61
Work Zone speed limit (mph)	60	50	40	25	25	25	60	60	50	40	25	10
Wk Zone Cap (vphpl)	1510	1050	1050	1050	1050	1050	1510	1510	1510	1050	1050	1050
Rehab #1 & #2	PRODUCTIVITY RATE = 2.8											
Work Zone Duration	0.9	0.4	0.4	0.4	0.4	0.4	1.3	0.9	0.9	0.4	0.4	0.4
# Lanes Open in Each Dir. During Work	1	0.5	0.5	0.5	0.5	0.5	2	1	1	0.5	0.5	0.5
Activity Service Life	10	10	10	10	10	10	10	10	10	10	10	10
Maintenance Frequency (years)	10	10	10	10	10	10	10	10	10	10	10	10
Work Zone Length (miles)	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61
Work Zone speed limit (mph)	60	50	40	25	25	25	60	60	50	40	25	10
Wk Zone Cap (vphpl)	1510	1050	1050	1050	1050	1050	1510	1510	1510	1050	1050	1050
Value of Time (VOT) for Passenger Cars ($/hour)	$10.46	VOT for Single Unit Trucks ($/hour)	27.83	VOT for Comb Trucks ($/hour)	27.83	Loss of fuel due to congested traffic (LOFCT) for Cars (L/mi)		0.08	LOFCT Trucks (L/mi)	.53	LOFCT Trucks (L/mi)	0.53

Table A.3 – Key MEPDG roughness values for each roadway classification in two climate zones (m/km)

Rural Network / Temperate Climate

Year	Interstates	Other Principal Arterials	Minor Arterials	Major Collectors	Minor Collectors	Local Roads
1	63	63	63	63	63	63
20	67.5	65.3	95.5	95.5	95.5	95.5
21	63	63	63	63	63	63
30	64.7	63.9	76.7	76.7	76.7	76.7
31	63	63	63	63	63	63
40	64.7	63.9	76.7	76.7	76.7	76.7

Urban Network / Temperate Climate

Year	Interstates	Other Freeways and Expressways	Other Principal Arterials	Minor Arterials	Collectors	Local Roads
1	63	63	63	63	63	63
20	68.4	67.5	67.7	65.3	95.5	95.5
21	63	63	63	63	63	63
30	65.2	64.7	64.6	63.9	76.7	76.7
31	63	63	63	63	63	63
40	65.2	64.7	64.6	63.9	76.7	76.7

Rural Network / Extreme Climate

Year	Interstates	Other Principal Arterials	Minor Arterials	Major Collectors	Minor Collectors	Local Roads
1	63	63	63	63	63	63
20	108	102.6	147.4	147.4	147.4	147.4
21	63	63	63	63	63	63
30	83.8	81.3	100.1	100.1	100.1	100.1
31	63	63	63	63	63	63
40	83.8	81.3	100.1	100.1	100.1	100.1

Urban Network / Extreme Climate

Year	Interstates	Other Freeways and Expressways	Other Principal Arterials	Minor Arterials	Collectors	Local Roads
1	63	63	63	63	63	63
20	110.3	108	106.9	102.6	147.4	147.4
21	63	63	63	63	63	63
30	84.9	83.8	82.7	81.3	100.1	100.1
31	63	63	63	63	63	63
40	84.9	83.8	82.7	81.3	100.1	100.1

Table A.4 – Life-cycle GWP per km for rural roadways (Mg CO_2e)

Roadway classification	Aggregate Mining	Aggregate Transport	Albedo	Carbonation	Cement Production	Cement Transport	Concrete Mixing	End of Life Disposal	End of Life Transport	Fly Ash	Fuel Consumed from Roughness	Mix Transport	Onsite Equipment	Pavement Demolition	Pavement Lighting	Pavement Rehabilitation	Steel Production	Steel Transport	Traffic Delay	Water Production and Transport	Total
Interstate	72	204	0	-44	2063	78	9	194	185	2	613	60	44	69	0	40	105	2	81	8	3786
Other Principal Arterial	32	76	0	-23	768	29	4	72	77	1	143	22	16	26	0	20	46	0	8	3	1331
Minor Arterial	30	72	0	-23	686	26	3	65	72	1	137	20	15	23	0	20	0	0	4	3	1162
Major Collector	24	56	0	-20	466	18	2	44	55	0	52	14	10	16	0	18	0	0	2	2	765
Minor Collector	5	19	0	-19	385	15	2	36	21	0	24	11	8	13	0	18	0	0	1	1	541
Local Road	3	12	0	-15	247	9	1	23	13	0	8	7	5	8	0	18	0	0	0	1	343

Table A.5 – Life-cycle GWP per mi for rural roadways (t CO_2e)

Roadway classification	Aggregate Mining	Aggregate Transport	Albedo	Carbonation	Cement Production	Cement Transport	Concrete Mixing	End of Life Disposal	End of Life Transport	Fly Ash	Fuel Consumed from Roughness	Mix Transport	Onsite Equipment	Pavement Demolition	Pavement Lighting	Pavement Rehabilitation	Steel Production	Steel Transport	Traffic Delay	Water Production and Transport	Total
Interstate	128	362	0	-78	3660	138	16	344	328	4	1087	106	78	122	0	71	186	4	144	13	6715
Other Principal Arterial	57	135	0	-41	1362	51	7	128	137	2	254	39	28	46	0	35	82	0	14	5	2363
Minor Arterial	53	128	0	-41	1217	46	5	115	128	1	243	35	27	41	0	35	0	0	7	4	2061
Major Collector	43	99	0	-35	827	32	4	78	98	1	92	25	18	28	0	32	0	0	4	3	1358
Minor Collector	9	34	0	-34	683	27	4	64	37	1	43	20	14	23	0	32	0	0	2	2	960
Local Road	5	21	0	-27	438	16	2	41	23	1	14	12	9	14	0	32	0	0	0	2	608

Table A.6 – Life-cycle GWP per km for urban roadways (Mg CO_2e)

Roadway classification	Aggregate Mining	Aggregate Transport	Albedo	Carbonation	Cement Production	Cement Transport	Concrete Mixing	End of Life Disposal	End of Life Transport	Fly Ash	Fuel Consumed from Roughness	Mix Transport	Onsite Equipment	Pavement Demolition	Pavement Lighting	Pavement Rehabilitation	Steel Production	Steel Transport	Traffic Delay	Water Production and Transport	Total
Interstate	93	236	0	-58	2854	108	13	269	248	3	1930	83	61	96	0	60	155	1	93	10	6302
Other Freeway / Expressway	69	167	0	-44	1907	72	9	180	176	2	1199	55	41	64	0	40	105	1	23	7	4111
Other Principal Arterial	44	124	0	-37	1271	48	6	120	113	1	435	37	27	43	0	40	74	0	33	5	2391
Minor Arterial	29	79	0	-23	739	28	3	70	71	1	199	21	16	25	0	20	46	0	9	3	1339
Collector	7	29	0	-22	602	23	3	57	31	1	171	18	13	20	0	18	0	0	5	2	981
Local Road	4	19	0	-19	388	15	2	37	20	0	40	11	8	13	0	15	0	0	2	1	559

Table A.7 – Life-cycle GWP per mi for urban roadways (t CO_2e)

Roadway classification	Aggregate Mining	Aggregate Transport	Albedo	Carbonation	Cement Production	Cement Transport	Concrete Mixing	End of Life Disposal	End of Life Transport	Fly Ash	Fuel Consumed from Roughness	Mix Transport	Onsite Equipment	Pavement Demolition	Pavement Lighting	Pavement Rehabilitation	Steel Production	Steel Transport	Traffic Delay	Water Production and Transport	Total
Interstate	165	419	0	-103	5063	192	23	477	440	6	3424	147	108	170	0	106	275	2	165	18	11150
Other Freeway / Expressway	122	296	0	-78	3383	128	16	319	312	4	2127	98	73	114	0	71	186	2	41	12	7273
Other Principal Arterial	78	220	0	-66	2255	85	11	213	200	3	772	66	48	76	0	71	131	0	59	8	4229
Minor Arterial	51	140	0	-41	1311	50	5	124	126	2	353	37	28	44	0	35	82	0	16	5	2368
Collector	12	51	0	-39	1068	41	5	101	55	1	303	32	23	35	0	32	0	0	9	4	1733
Local Road	7	34	0	-34	688	27	4	66	35	1	71	20	14	23	0	27	0	0	4	3	988

Table A.8 – Analyzed pavement designs: rural roadways (U.S. units See Table 2.2 for SI units)

	Interstate	Principal Arterial	Minor Arterial	Major Collector	Minor Collector	Local
Function definition						
AADT(1)	22074	6414	3084	1219	574	177
AADTT(2)	4415	706	308	85	40	12
Total lanes	4(3)	2	2	2	2	2
Lane width (ft)	12	12	12	11	11	2.7
Corresponding AASHTO design						
Shoulder width (ft)	4 / 10(4)	8	8	6	5	2
Concrete thickness (in)	11.5	8	7.5	6	5(7)	4(7)
Base thickness (in)	6	6	6	6	0	0
Steel dowel diameter (in)	1.5	1.25	-	-	-	-

Table A.9 – Analyzed pavement designs: urban roadways (U.S. units, See Table 2.3 for SI units)

	Interstate	Freeway	Principal Arterial	Minor Arterial	Collector	Local
Function definition						
AADT(1)	78789	53809	19631	9729	4221	980
AADTT(2)	6303	2152	785	389	169	39
Total lanes	6(3)	4(3)	4	2	2	2
Lane width (ft)	12	12	12	12	11	9
Corresponding AASHTO design						
Shoulder width (ft)	10	4 / 10(4)	8(5)	8(5)	8(5,6)	7(5,6)
Concrete thickness (in)	12	11	8.5	7	6.5	5(7)
Base thickness (in)	6	6	6	6	0	0
Steel dowel diameter (in)	1.5	1.5	1.25	1.25	-	-

[1] AADT: annual average daily traffic (two way)
[2] AADTT: annual average daily truck traffic (two way)
[3] Two carriageways with separating median
[4] Inner / outer shoulder width. Includes aggregate in concrete, base, and foreslope elements. Minimum foreslope of 4H:1V is used.
[5] Urban curb and gutter design with no foreslope
[6] Shoulders are parking lanes
[7] These pavements are thinner than some states allow. However, the AASHTO '93 design procedure was still followed to remain consistent.
[8] Dowel length is 18", lateral spacing is 9", steel density is 490 lb/ft^3, and concrete slab length is 15 ft.

Table A.10 – Material inputs per km [per mi] for rural roadways

	Interstate	Freeway	Principal Arterial	Minor Arterial	Collector	Local
Shoulder surface area (m^2) [ft^2]	8534 [147833]	4877 [84483]	4877 [844483]	3658 [63367]	3048 [52800]	1219 [21117]
Mainline surface area (m^2) [ft^2]	14630 [253433]	7315 [126717]	7315 [126717]	6706 [116167]	6706 [116167]	6706 [116167]
Concrete volume (m^3) [yd^3]	6766 [14242]	2477 [5214]	2323 [4890]	1580 [3326]	1239 [2608]	805 [1694]
Concrete mass (Mg) [t]	15561 [27605]	5797 [10284]	5178 [9186]	3515 [6236]	2902 [5148]	1865 [3309]
- Cement mass (Mg) [t]	2223 [3944]	828 [1469]	739 [1311]	502 [891]	415 [736]	266 [472]
- Fly ash mass (Mg) [t]	247 [438]	92 [163]	82 [145]	56 [99]	46 [82]	30 [53]
- Water mass (Mg) [t]	1000 [1774]	372 [660]	333 [591]	226 [401]	187 [332]	120 [213]
Aggregate[1] mass (Mg) [t]	20259 [35939]	8403 [14907]	8102 [14373]	6245 [11079]	1967 [3489]	1277 [2265]
Steel mass (Mg) [t]	85 [151]	37 [66]	-	-	-	-

[1] Includes aggregate in concrete, base, and foreslope elements

Table A.11 – Material inputs per km [per mi] for urban roadways

	Interstate	Freeway	Principal Arterial	Minor Arterial	Collector	Local
Shoulder surface area (m^2) [ft^2]	12192 [211200]	8534 [147833]	4877 [84483]	4877 [84483]	4877 [84483]	4267 [73917]
Mainline surface area (m^2) [ft^2]	21946 [380167]	14630 [253433]	14630 [253433]	7315 [126717]	6706 [116167]	5486 [95033]
Concrete volume (m^3) [yd^3]	10405 [21902]	6472 [13623]	4211 [8864]	2168 [4564]	1912 [4025]	1239 [2608]
Concrete mass (Mg) [t]	21530 [38194]	14385 [25519]	9591 [17014]	5572 [9885]	4542 [8057]	2925 [5189]
- Cement mass (Mg) [t]	3075 [5455]	2055 [3646]	1370 [2430]	796 [1412]	649 [1151]	418 [742]
- Fly ash mass (Mg) [t]	342 [607]	228 [404]	152 [270]	88 [156]	72 [128]	46 [82]
- Water mass (Mg) [t]	1384 [2455]	925 [1641]	616 [1093]	358 [635]	292 [518]	188 [334]
Aggregate[1] mass (Mg) [t]	29186 [51776]	19645 [34850]	13279 [23557]	7804 [13844]	3055 [5420]	1967 [3489]
Steel mass (Mg) [t]	125 [222]	85 [151]	60 [106]	37 [66]	-	-

[1] Includes aggregate in concrete, base, and foreslope elements

Table A.12 – MEPDG concrete pavement designs compared to AASHTO '93 equivalents for Oxnard, CA (U.S. units, see Table 2.10 for SI units)

Rural Network			*Urban Network*		
Roadway class	AASHTO '93	MEPDG	Roadway class	AASHTO '93	MEPDG
Interstate	11.5 in JPCP 6 in base 1.5 in dowels	9 in JPCP 4 in base 1.5 in dowels	Interstate	12 in JPCP 6 in base 1.5 in dowels	9 in JPCP 6 in base 1.5 in dowels
Other Principal Arterial	8 in JPCP 6 in base 1.5 in dowels	7.5 in JPCP 4 in base 1 in dowels	Other Freeway / Expressway	11 in JPCP 6 in base 1.5 in dowels	8.5 in JPCP 6 in base 1.5 in dowels
Minor Arterial	7.5 in JPCP 6 in base No dowels	7 in JPCP 4 in base No dowels	Other Principal Arterial	8.5 JPCP 6 in base 1.25 in dowels	7.5 in JPCP 4 in base 1.25 in dowels

Table A.13 – Costs and other data used to conduct the CEA for the GHG emission reduction strategies (U.S. units, see Table 2.13 for SI units)

Parameter	Best estimate	Low estimate	High estimate	Reference (if applicable)
Cement ($/Mg)	$93			USGS (2009)
Fly ash ($/Mg)	$45	$23	$59	Tikalsky et al. (2011)
Truck transport ($/t-mi)	$0.18			
Extra aggregate haul (mi)	31	0	124	
Recycled concrete value ($/t)	$6.74			USGS (2008)
Annual carrying cost (%/t/yr)	25%	20%	40%	Hendrickson (2008)
EOL carbonation duration (y)	1	0.3	30	
EOL carbonation (% of calcination)	28%	20%	44%	Doodoo et al. (2009)
Grinding cost ($/yd^2)	$3.60	$3.34	$4.18	Caltrans (2011)
Concrete pavement ($/yd^3)	$162	$115	$209	Caltrans (2011)
Aggregate base ($/yd^3)	$63	$39	$87	Caltrans (2011)
Steel dowel bar ($/yd^3)	$126			USGS (2010)

Table A.14 – Summary of inputs and results for the cost effectiveness of GHG reduction strategies (U.S. units, see Table 2.14 for SI units)

	Increased fly ash	White aggregates	EOL stockpiling	Extra rehabilitation	MEPDG case study
Reduction category	Embodied emissions	Albedo	Carbonation	PVI	Embodied emissions
Key assumption(s)	10% → 30% fly ash replacement	- 0.19 albedo increase - 50 km extra distance	1-year EOL exposure	Additional grinding at year 10	Equivalent design life as AASHTO '93 design
Key driver(s)	- Fly ash cost* - Fly ash content	- Longer transportation distance* - Albedo increase of white aggregates	- Exposure time* - Annual carrying cost*	- Grinding cost* - Concrete cost* - Grinding schedule - "Roughness → rolling resistance" factor	- Material unit costs* - M&R schedule - Extent of overdesign
Key cost(s)	Fly ash cost: $45/t	Transportation unit cost: $0.18/t-mi	Annual carrying cost: 25% of market value	- Grinding cost: $3.60/yd^2 - Concrete cost: $162/yd^3	- Concrete cost: $162/yd^3* - Base cost: $63/yd^3
Emissions saved (t CO_2e saved/mi)	110–1,200	270–820	57–730	18–1,400	160–1,600
Cost range (per mi)	(-$47,000)–(-$3,500)	$9,700–$120,000	$5,100–$68,000	$56,000–$230,000	(-$900,000)–(-$64,000)
Cost effectiveness range ($/t CO_2e saved)	(-$39)–(-$31)	$37–$150	$91	$160–$6,700	(-$560)–(-$340)
Most cost effective (MCE)	Urban interstates	Rural local roads	Equal across all classifications	Urban interstates	Urban interstates
Sensitivity parameters	Fly ash cost: $23–$59/t	Extra transportation distance: 0–124 mi	- Exposure time: 4 month, 1 year, 30 years - Annual carrying cost: 20–40%	- Grinding: $3.34–$4.18/yd^2 - Concrete: $120–210/yd^3	- Concrete: $120–$210/yd^3 - Base: $39–$87/t
Sensitivity of MCE ($/t CO_2e saved)	(-$64)–(-$31)	$0–$160	$30–$2,700	$140 –$190	(-$720)–(-$400)

* indicates that a sensitivity analysis is conducted for this driving parameter

APPENDIX B. SUPPORTING INFORMATION FOR SECTION 3

Table B.1 – List of major studies on the effect of pavement type on fuel consumption of vehicles. Increased fuel consumption on an asphalt pavement, compared to a concrete pavement (U.S. units, see Table 3.1 for SI units)

Study	Year	Vehicle Type	Speed (mph)	IRI Value (in/mile)	Increased Fuel Consumption (gal/100mile)	Source
Zaniewski	1982	Trucks	10-68	63-424	2.5-3.6	Zaniewski et al. (1982)
Zaniewski	1982	Cars	10-68	63-424	-0.3-0.6	Zaniewski et al. (1982)
NRC I	2000	Trucks	62	63-221	1.7-1.8	Taylor et al. (2000)
NRC I	2000	Trucks	37	63-221	0.7-0.8	Taylor et al. (2000)
NRC II	2002	Trucks	62	63-221	0.6-1	G.W. Taylor Consulting (2002)
NRC II	2002	Trucks	37	63-221	0.6-1	G.W. Taylor Consulting (2002)
NPC	2002	Trucks	50	-	0.01-0.1	NPC (2002)
De Graaff	1999	Trucks	56	-	-0.08-0.08	De Graaff (1999)
NRC III	2006	Trucks	62	63	0.2-0.3	Taylor et al. (2006)
NRC III	2006	Empty Trucks	62	63	0.1-0.2	Taylor et al. (2006)
NRC III	2006	Full Trucks	37	63	0.2-0.21	Taylor et al. (2006)
NRC III	2006	Cars	62	63	0.08-0.12	Taylor et al. (2006)
U Texas	2009	Cars	37	171-323	0.2-0.38	Ardakani et al. (2009)
Michigan SU	2010	Trucks	37	-	0.4	Zaabar et al. (2010)

B.1 Beam on Damped Elastic Foundation

The governing differential equation for an infinite beam on an elastic foundation in fixed Cartesian coordinates *{x,y}* at time t is represented in equation [B.1] (Kim and Roesset 2003).

$$[\text{B.1}] \quad EI\frac{\partial^4 y(x,t)}{\partial x^4} + m\frac{\partial^2 y(x,t)}{\partial t^2} + ky(x,t) = q(x,t)$$

where E is the Young's modulus of elasticity, I is the moment of inertia, m is the mass of the beam per unit length, k is the stiffness of the foundation per unit length, and $q(x,t)$ is the external load per unit length. To be consistent with Kim and Roesset (2003) and Sun (2001) the top layer elastic modulus is referred to as E (rather than E_t) and the subgrade modulus is referred to as k (rather than E_s) in this section.

If the load, $q(x,t)$ is moving in the positive x direction with a velocity of V, a moving coordinate η can be defined as $\eta = x - Vt$. Substituting this new coordinate system into equation [B.1] gives

$$[\text{B.2}] \quad EI\frac{\partial^4 y(\eta,t)}{\partial \eta^4} + m\left(\frac{\partial^2 y(\eta,t)}{\partial t^2} - 2V\frac{\partial^2 y(\eta,t)}{\partial t \partial \eta} + V^2\frac{\partial^2 y(\eta,t)}{\partial \eta^2}\right) + ky(\eta,t) = q(\eta,t)$$

If a moving load of constant amplitude is assumed, and ξ is defined as the transformed field of η (moving space), the dynamic displacement response can be obtained using the inverse Fourier transform

[B.3] $$y(\eta) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{Q(\xi)}{EI\xi^4 - mV^2\xi^2 + k(1+2i\zeta)} e^{i\xi\eta} d\xi$$

where $Q(\xi)$ is the transformed load and is defined by equation [B-4]. Also, the term $2i\zeta$corresponds to the hysteretic damping present in soil within the subgrade, where ζ is the damping ratio, as suggested by Kim & Roesset (2003).

[B.4] $$Q(\xi) = q\int_{-a/2}^{a/2} e^{-i\xi\eta} d\eta$$

where a is the loading width shown in Figure 3.2.

B.2 Solution Strategy

Equation [B.3] can be solved using numerical and analytical methods. To evaluate this integral analytically, poles of the integrand are identified using equation [B.5].

[B.5] $$\xi^2 = \frac{mV^2 \pm \sqrt{m^2V^4 - 4\,EI\,k(1+2i\zeta)}}{2EI}$$

Every pole and its order are isolated and given in closed form. The theorem of residue is then applied to represent the generalized integral in form of contour integral in the complex plane (Sun, 2001). The contour is presented in Figure 3.3 and the solution is obtained using equation [B.6]

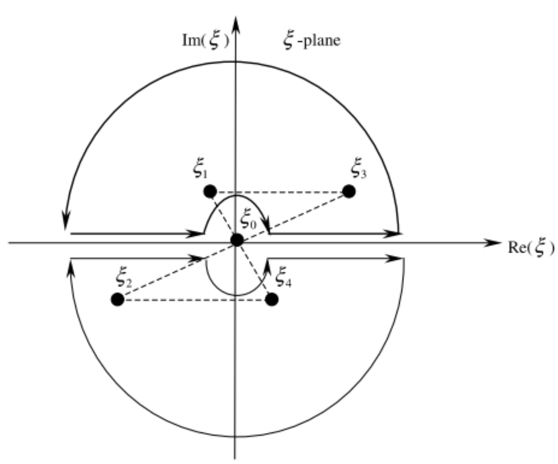

Figure B.1 – Representative contour for the integral (Sun, 2001)

[B.6] $p.v.\int_{-\infty}^{\infty}\frac{e^{i\xi(\eta-a)}-e^{i\xi(\eta+a)}}{\xi(EI\xi^4-mV^2\xi^2+k(1+2i\zeta))}d\xi =$

$$\frac{2\pi i}{EI}\sum_{Im\,\xi_j>0} Res\left\{\frac{e^{i\xi(\eta-a)}-e^{i\xi(\eta+a)}}{\xi\prod_{j=0}^{4}(\xi-\xi_j)}\right\}+\frac{\pi i}{EI}\sum_{Im\,\xi_j=0} Res\left\{\frac{e^{i\xi(\eta-a)}-e^{i\xi(\eta+a)}}{\xi\prod_{j=0}^{4}(\xi-\xi_j)}\right\}$$

where *p.v.* indicates the principal value of the integrand, and *Im* represents imaginary parts of the complex variable ξ_j (Sun, 2001).