THE DEVELOPMENT OF A REGIONAL INVENTORY DATABASE FOR THE MATERIAL PHASE OF THE PAVEMENT LIFE-CYCLE WITH UPDATED VEHICLE EMISSION FACTORS USING MOVES

BY

SEUNGGU KANG

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Civil Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2013

Urbana, Illinois

Advisers:

Professor Imad L. Al-Qadi, Adviser
Research Assistant Professor Hasan Ozer, Co-adviser

ABSTRACT

Over the past few decades, the growing interest in pavement sustainability has led researchers in government agencies, industries, and academia to develop various sustainability rating systems and life-cycle assessment (LCA) tools for roadways and pavements. However, many of the existing pavement LCA tools use outdated databases and, at present, there are no regional LCA tools available. This study focuses on regionalizing the pavement LCA by collecting and analyzing local data from the state of Illinois. This study attempted to develop a life-cycle inventory (LCI) database. In addition, an inventory analysis for various pavement materials, based on the ISO 14044 guidelines, was performed. As such, the greenhouse gas (GHG) emissions and energy consumption per unit mass of materials were computed and combined to develop a regional LCI database. The study updated the existing vehicle emission factors through simulations using EPA's newest vehicle emission simulator, MOVES. As a result, accurate emission factors for six various types of mobile vehicles were computed and presented.

ACKNOWLEDGEMENTS

This great opportunity to work on the Illinois Tollway pavement sustainability project would have been impossible if it were not for Professor Imad Al-Qadi. I am very grateful to Professor Imad Al-Qadi for giving me this opportunity and I truly admire his passion and expertise toward his profession.

Last one year was one of the most important periods in my life. I have had a wonderful experience of meeting and working with intelligent and enthusiastic researchers at the Illinois Center for Transportation. I was lucky to be able to work with Dr. Hasan Ozer, who always encouraged me and provided me with a direction for the research. I also want to thank Songsu Son for his advice not only on my research but also for my life. I am also thankful to my project colleague, Rebekah Yang, other co-workers and staff members at the Illinois Center for Transportation for the support.

I am also thankful for the Illinois Tollway for providing us financial support to work on the pavement sustainability project. This research opportunity has stimulated my academic interest in the life-cycle assessment of pavements.

The support from my parents, Seongjoo Kang and Aeja Choi, my sister, and other family members was crucial for me being able to study at the University of Illinois and I want to thank them for their love and trust. I also want to thank my friends who have encouraged me with many heartfelt messages.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION ... 1

1.1 Background of Life-Cycle Assessment (LCA) ... 2
1.2 Problem Statement ... 4
1.3 Research Objective ... 5
1.4 Impact of the Work ... 5
1.5 Scope of Study ... 5

CHAPTER 2. LITERATURE REVIEW ... 7

2.1 Life-Cycle Assessment for Pavements ... 7
2.2 Current Pavement Life-Cycle Assessment Studies ... 13

CHAPTER 3. GOAL AND SCOPE DEFINITION OF LIFE-CYCLE ASSESSMENT ... 17

3.1 Goal of the Pavement Life-Cycle Assessment ... 17
3.2 Scope of the Pavement Life-Cycle Assessment ... 17
3.3 Major Assumptions Adopted in the Development of Life-Cycle Assessment ... 21

CHAPTER 4. LIFE-CYCLE INVENTORY ANALYSIS ... 24

4.1 Life-Cycle Inventory Items ... 24
4.2 Data Collection from Regional Sources ... 24
4.3 Summary of the Collected Data ... 38
4.4 Impact Assessment ... 39

CHAPTER 5. MOBILE VEHICLE EMISSION ESTIMATION ... 40

5.1 Introduction to MOVES Software ... 40
5.2 Updated Emission Factors for Mobile Vehicles ... 48
5.3 Validation of Updated Emission Factors ... 52

CHAPTER 6. CASE STUDIES USING LCA TOOL ... 54

6.1 Background on Case Studies ... 54
6.2 Analysis of a Case Study Using the LCA Tool ... 56
6.3 Sensitivity to Transportation Distances and Emission Factor Choices ... 57

CHAPTER 7. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS ... 61

7.1 Summary ... 61
7.2 Findings and Conclusions ... 61
7.3 Recommendations for Future Research ... 63

REFERENCES ... 65

APPENDIX A ... 69

APPENDIX B ... 71

APPENDIX C ... 74

APPENDIX D ... 77

CHAPTER 1. INTRODUCTION

Transportation is one of the most important sectors of the national economy, accounting for nearly 10 percent of the Gross Domestic Product (GDP) of the United States in 2002 (U.S. DOT, 2006). As the demand for the movement of private and commercial goods has rapidly grown over the past few decades the role of transportation has become even more important. About 70 percent of all goods by weight in the U.S. are transported by trucks, a demand that makes the building and maintaining of an adequate roadway infrastructure crucial (U.S. DOT, 2010).

Construction of a roadway infrastructure requires a vast amount of resources. The total road length in the U.S. in 2007 was 4,032,126 miles. Hence, a considerable budget of many States' Department of Transportation is spent every year in rehabilitating and expanding existing roadways (FHWA, 2012). Road construction is energy and natural resources demanding activity that uses various materials such as asphalt binder, Portland cement, and aggregates. Pavement construction and material production are a very energy intensive process because of their consumption of fossil fuels or use of electricity, which in turn produces a large amount of emissions into the environment.

There are numerous ways of improving the sustainability of pavements. Some of the simplest yet most effective ways to improve the sustainability of pavement material production and construction include the following:

- Increasing the quality of production in plants and during construction
- Increasing the efficiency of production in plants
- Using recycled material alternatives when these material s are available and cost-effective

A metric is needed to quantify environmental burdens of a product system or a production process. Life-cycle assessment (LCA) has been successfully used in the recent years to assess the environmental impact of different life-cycle stages of pavements. Earlier studies by Stripple (2001) and Santero (2009) contributed to the development of pavement LCA framework. LCA is a technique that will be used throughout this study to quantify emissions for any process in the life-cycle of roadways. The study focuses on the data collection and life-cycle inventory (LCI) database development stage of pavement LCA.

1.1 Background of Life-Cycle Assessment (LCA)

The history of LCA traces back to the 1960s. Potential resource depletion and environmental degradation motivated people to develop a way to examine the current resources management and to predict future energy use. In 1972, a book entitled *The Limits to Growth* was published that raised a question to the public about sustainability. Its main message was that the global society is likely to overshoot its available resources and collapse because of reaction delays and the planetary physical limitations; thus early action is necessary to keep the globe sustainable (Meadows et al., 1972). The early foundation of inventory analysis was prepared by researchers for the Coca-Cola Company in 1969, and the first evolutionary impact assessment was introduced in 1998 (U.S. EPA, 2006). The standard guidelines for LCA were developed in 1997 by the International Standards Organization (ISO). According to the ISO, the increased public awareness of the importance of environmental protection and impacts associated with products manufactured and consumed led to the development of the methods to better comprehend and reduce these impacts (ISO, 1997).

ISO guidelines divide the basic LCA framework into four different stages: goal and scope definition, inventory analysis, impact assessment and interpretation. The goal and scope of an LCA study should clearly state the intended application and system boundaries as well as any assumptions made in the study. In life-cycle inventory analysis, data collection and quantification of inputs and outputs of a product system are the main tasks (ISO, 1997). In impact assessment, the data from inventory analysis are classified into various impact categories to evaluate potential environmental impacts. Based on the results from inventory analysis and impact assessment, findings can be stated in the conclusion of the study through the interpretation stage (ISO, 1997). These findings of an LCA study may be used for decision making or strategic planning. Figure 1.1 describes how each phase in the LCA framework interacts.

Although LCA was first introduced several decades ago, its definition is not yet widely known. Various organizations have different definitions for LCA, but most of these definitions are essentially very similar. The ISO defines LCA as the “compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life-cycle” (U.S. EPA, 2006). Another definition given by the Environmental Protection Agency (EPA) is “a cradle-to grave approach for assessing industrial systems that evaluate all stages of a product’s life and provide a comprehensive view of the environmental aspects of the product or process” (U.S. EPA, 2006). Common words found in both definitions are *environmental* and *life* and with these words we can simply re-define LCA as the measurement of environmental impacts of a product during its life-cycle. The reason LCA is a cradle-to-grave approach is that LCA accounts for all steps from upstream processes to the end-of-life (EOL) of a product. Upstream processes usually refer to raw materials extraction/acquisition and material processing.

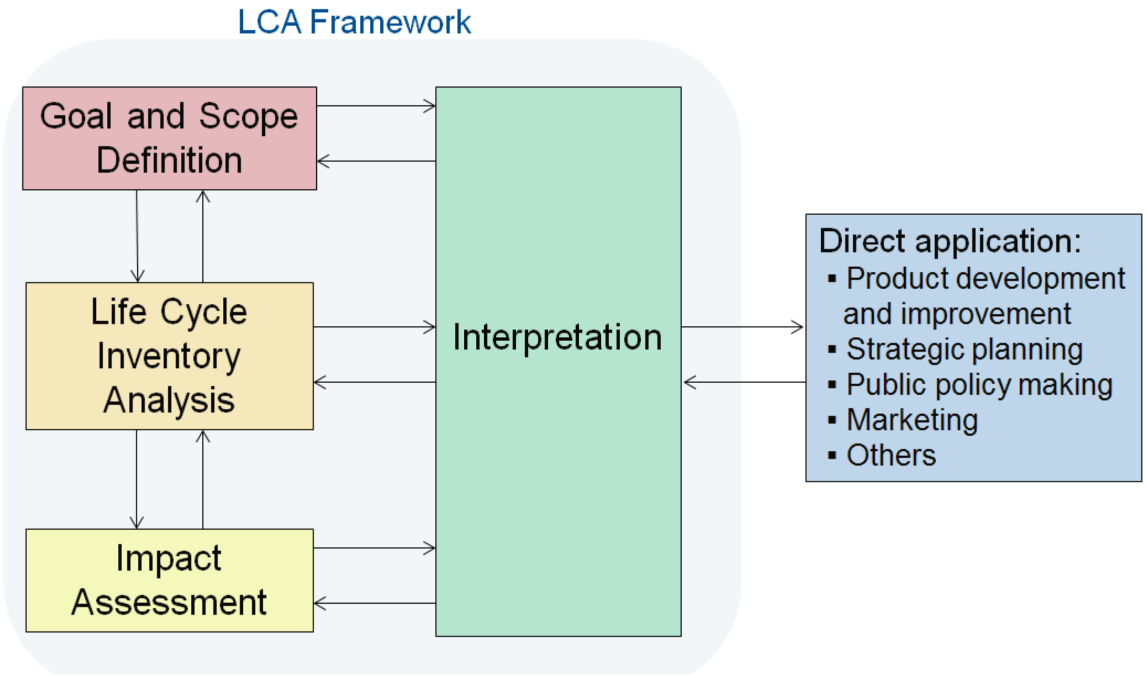


Figure 1.1 Interaction between LCA phases and application (after ISO, 1997)

As mentioned above, this study introduces the life-cycle of pavements, so the materials will be exactly those that compose a pavement. For example, in the case of asphalt binder, crude oil extraction is a raw materials extraction/acquisition activity, and refining crude oil to produce asphalt binder is a material processing stage. Because LCA is used to quantify environmental impacts, any emission or energy use during any stage of the pavements life-cycle must be recorded.

Between the upstream processes and the EOL, there are other LCA phases such as manufacturing, construction, use, and maintenance. For example, for hot-mix asphalt (HMA) production, mixing asphalt binder with aggregates and filler can be considered as part of the material production stage. Once HMA is brought to a construction site, and placed with paving equipment this process can be considered to be within the construction stage of LCA. As pavements deteriorate with time, severe distresses such as fatigue damage and rutting appear. Depending on pavement conditions such as surface roughness and deformations the amount of vehicle emissions changes accordingly. Studying the relationship between pavement roughness or rolling resistance and vehicle emissions is an example of pavement use phase research. Since regular rehabilitation activities take place during the life-cycle of pavements, the emissions and energy use during the maintenance stage should be recorded. The EOL entails either landfilling or recycling the deteriorated pavements. The flow of LCA stages is illustrated in Figure 1.2.

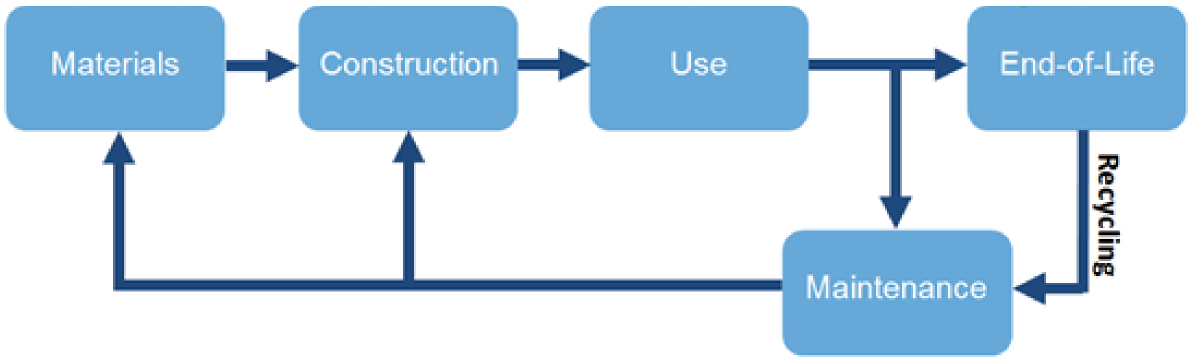


Figure 1.2 The flow diagram of LCA phases (after Santero et al., 2011)

LCA is not only crucial to understanding the environmental impact of a product; it provides other important benefits. Some of the advantages of using LCA include the following:

- The ability to quantify environmental impacts, as compared to conventional rating systems that qualitatively measure sustainability.
- Providing the ability to identify the stage at which a product's influence on environmental is the greatest (i.e., the energy consumption in the material phase being greater than that in the construction phase).
- Allowing for the comparison of the environmental impact of construction alternatives (i.e. PCC overlay vs. HMA overlay), thus allowing for the selection of a more sustainable alternative.

Despite the fact that LCA has many benefits and is a very systematic and standardized method, it has its limitations:

- Conducting an LCA study is time intensive and somewhat costly.
- Data collected during the LCI process must be checked for reliability.
- Some data may not be available; as an alternative, an appropriate adjustment should be made.

1.2 Problem Statement

There are a number of qualitative sustainability rating systems developed by governmental, commercial and non-profit organizations that measure the sustainability of roadways, including *Leadership in Energy and Environmental Design (LEED)*, offered by the U.S. Green Building Council (USGBC) and *Infrastructure Voluntary Evaluation Sustainability Tool (INVEST)*, overseen by the Federal

Highway Administration (FHWA). However, there are a limited number of tools that quantitatively measure the sustainability of roadways. When it comes to pavements, even fewer tools are available and most of them use outdated databases or can only estimate limited emissions. Furthermore, if the scope is focused on an Illinois regional scale analysis, no tools currently exist. Therefore, there is a need to develop a regional scale tool tailored for pavements to quantify its relationship with the environment. In order to develop this tool, it is necessary to create an LCI database that reflects regional data collected from the manufacturers and suppliers in or near the state of Illinois in addition to the regional data for fuels and energy resources.

1.3 Research Objective

The main objective of this study is to develop an LCI to quantify the relationship between the environment and pavements. To achieve this objective, the following tasks were addressed:

1) Investigation of environmental emissions and energy use associated with the material stage of flexible and rigid pavements. The use of regionally collected data is highly recommended in order to represent a regional scale analysis. However, reported data from the literature can also be used if there is any data missing.
2) The estimation of mobile vehicle emissions from material transportation using Mobile Vehicle Emission Simulator (MOVES) software developed by the EPA.

1.4 Impact of the Work

As there are a few regional scale pavement LCA studies known, this study will provide a useful component of a comprehensive methodology for a pavement LCA study in Illinois. By preparing and continuously updating the LCI database, it is expected that the LCA study will provide more accurate and up-to-date environmental impacts. Also, by incorporating recent version of the EPA's mobile vehicle emission software in the study, the emission factors for hauling materials will be estimated more accurately.

1.5 Scope of Study

Chapter 1 presents an introduction to pavement LCA as well as the objective and impact of the study. A comprehensive literature review of major pavement material LCI, existing pavement LCA and tools was presented to assess the current status of pavement LCA in Chapter 2. The goal and scope definition for pavement LCA describes the structure, functional unit, system boundaries of pavement LCA as well as major assumptions made throughout the study in Chapter 3. Chapter 4 explains the procedure to develop a regionalized pavement LCI database and validates the quality of regionally collected data by comparing them to the literature. In order to accurately predict vehicle emissions, simulations using the EPA's MOVES were performed in Chapter 5. A case study was performed based on the I-90 reconstruction project and a sensitivity analysis on hauling distances was performed in Chapter 6. Finally, conclusions were drawn and recommendations on future research were presented.

CHAPTER 2. LITERATURE REVIEW

The current literature comprises a number of LCA studies related to pavements and materials. It is noteworthy that each study has used a different methodology to conduct an LCA study. Desired outputs also vary slightly with each LCA study but greenhouse gas (GHG) emissions and energy are typical outputs of most LCA studies reviewed in this chapter.

2.1 Life-Cycle Assessment for Pavements

Pavement LCA studies have been conducted not only in the U.S. but also in other countries in Europe and Asia. This section explores both existing pavement LCA studies and raw material LCI studies. Because pavements are composed of various components, the LCI of every raw material contributing to these components should be included in material phase of any pavement LCA study. Material LCI studies usually lack the impact assessment process; however these LCI studies follow the standard ISO guidelines and are thus normally considered to be standalone LCA studies. Some of the commonly cited and known studies are selected and summarized in this chapter in a chronological order.

2.1.1 Stripple (2001)

Stripple (2001) investigated the energy consumption of a 1 km long road during its 40 year life span. An extensive life-cycle inventory study was presented including electricity generation, emissions from transportation and construction equipment, pavement material production and other minor roadway facilities. All LCA phases, except for the use phase, were covered in the study. The emissions and energy consumption of each LCA phase were graphically illustrated to identify the LCA phase that was most responsible for energy use and emissions.

Stripple's study showed that the total energy for construction, operation and maintenance of a 1 km long road during its 40 year life varied with the type of pavement. For flexible pavements, 23 TJ of energy was consumed whereas 27 TJ was consumed for rigid pavements. The energy consumption by traffic was also estimated. With an assumption of traffic of 5,000 cars per 24 hrs, the total energy by traffic was 229.2 TJ. For CO_2 emissions, the study showed that rigid pavements emitted about 2,750 Mg CO_2 compared to 2,050 Mg CO_2 for flexible pavements per unit length during the 40 year life span. Thus, flexible pavements were more environmentally friendly than rigid pavements in terms of CO_2 emission and energy use.

For some of inventory studies, a detailed computation procedure of emission and energy was unclear; however, Stripple listed a vast amount of inventory information in the appendix for other researchers, presenting a good reference for subsequent LCA studies.

2.1.2 Park et al. (2003)

In Park et al. (2003), a hybrid approach was used to conduct a LCA study on the life-cycle environmental impacts of highways. A hybrid approach uses economic input-output (EIO) LCA for upstream processes and conventional process LCA for downstream processes. The functional unit (FU) used was 1 km of a four lane highway. The study covered the following LCA stages: manufacturing of construction materials, construction, maintenance/repair, and the demolition/recycling.

An EIO energy analysis was used to quantify energy consumption by manufacturing construction materials for building highways. Regarding the maintenance of highway, the author argued that it was practically difficult to predict the pavement life span and determine its maintenance schedule. Park et al. simplified the maintenance stage by assuming that the pavement was milled and overlaid every seven years and repaved every 20 years. The energy consumption from operating the construction machinery was estimated from fuel usage and unit costs. The energy used for milling-overlay highway pavements was estimated using the EIO LCA tool.

In the EOL stage, the fuel demand and the working quantity of machinery were used to estimate the energy in demolition stage. Energy consumed in the recycling stage includes fuel demand for heavy machinery and electric power demand for the recycling plant. One of the interesting assumptions in this study was that the recycling percentage of construction & demolition debris was assumed to be 100% and all recycled materials were assumed to be reused in subbase layers for highways.

In conclusion, the total energy consumption through the life cycle of highways turned out to be 2,676.7 tons of oil equivalent (TOE) per FU. Of this value, 1,525.7 TOE (56.7% of total) was consumed in the material manufacturing stage. For environmental loads, manufacturing stage was the biggest source of NO_x, SO_2, and CO_2 emission followed by the maintenance and repair, construction, and the EOL stages.

2.1.3 Athena Institute (2006)

The Athena Institute (2006) compared the 50 year life cycle of HMA and Portland cement concrete (PCC) pavements in terms of energy consumption and global warming potential (GWP) in Canada. The results obtained were from four different road types: typical Canadian arterial roadways, high volume highways, Quebec urban freeway, and a section of the Highway 401 freeway in Ontario.

Material and maintenance phases were included in the study but the construction phase was excluded because its contribution was assumed to be relatively insignificant.

Applied Research Associates was retained to develop concrete and asphalt designs for typical roadways and highways in Canada. The AASHTO 1993 guide was used for both asphalt and concrete, and the Cement Association of Canada method was additionally used for concrete pavement design. In the case of asphalt, the effect of using recycled material was analyzed by comparing a virgin mix and a mix containing 20% reclaimed asphalt pavement (RAP). Also, asphalt binder's feedstock energy was separated from the total energy to determine its contribution.

The maintenance phase only considered major reconstructions or overlays and delayed less resource consuming activities such as crack sealing. In conclusion, the study showed that PCC pavement is advantageous both in terms of energy consumption and global warming potential emission regardless of the inclusion of feedstock energy.

2.1.4 PCA (2006)

A cement life-cycle inventory (LCI) study by PCA (2006) explored the energy use and CO_2 emission during the Portland cement (PC) manufacturing stage. The system boundary of the study neglected energy and emission from building a cement plant as well as upstream process for fuels and electricity. Transportation of raw materials to a manufacturing facility and cement production were considered.

PCA (2006) divided the cement production into four different stages: quarry and crush, raw material preparation, pyroprocessing, and finish grinding. The study investigated the energy use for both wet-process and dry-process PC plants. Typically, wet-process plant used more energy because the mix contained more moisture. The amount of energy required for wet processing is approximately Mbtu per ton of cement produced whereas approximately 3.6 Mbtu is required for the preheater and precalciner cement plant.

The LCI results from the study showed that the pyroprocessing used 88 % of the total fuel and 91% of the total energy. Half of the electricity was used by the finish grind stage. Almost 99% of CO_2 emissions were from the calcination process and fuel combustion for kilns. CO_2 emission from the wet-process plant was higher than the preheater/precalciner plant. Hence, the efficiency of the preheater/precalciner plant is higher in term of CO_2 emission.

2.1.5 PCA (2007)

PCA conducted another LCI study on Portland cement concrete (PCC) (PCA, 2007). The system boundaries of the study expanded beyond the 2006 cement LCI study, and included the raw material manufacturing stage, the transportation of raw materials to the plant, and the PCC mixing stage. Upstream processes for fuel and electricity generation as well as admixtures were neglected in the study.

The energy use and emission from aggregate production were estimated using the data from the U.S. Census Bureau and EPA AP-42 emission factors. The energy and emission information for cement was retrieved from PCA's 2006 cement LCI report. The plant energy was calculated from confidential LCI surveys of ready-mix concrete plants. By aggregating all energy and emission information from each process, 330 lb of CO_2 was emitted and 0.785 Mbtu of energy was used in the production of 1 yd^3 of concrete.

The author argued that data on raw material production and plant operation were reliable since these were peer reviewed by the PCA and other relevant allied groups.

2.1.6 Zhang et al. (2008)

The main objective of Zhang et al.'s (2008) study is to develop a model that assesses the sustainability indicators of pavement systems. The paper tries to evaluate the environmental friendliness of rigid pavement by quantifying the environmental impacts and costs throughout its life-cycle. Since the cost is considered, an integrated LCA and LCCA method was used and the life-cycle phases considered in the paper were material production/distribution, construction, maintenance, traffic delay, use, and end of life.

The study compares the environmental impacts of HMA, concrete, and ECC overlay systems. ECC is a fiber reinforced composite. The study used four commercially available tools as a part of its data collection process. SimaPro 7.0 was used to measure material environmental impact, MOBILE 6.2 was used for a vehicle emission, NONROAD was used as a construction equipment model, and the traffic flow model was provided by the University of Kentucky.

As a result of LCA, energy consumption by HMA turned out to be more than twice that of concrete and ECC pavements. In terms of GHG emission, HMA and concrete were at nearly the same level while ECC overlay had the lowest emission. Compared to the concrete and HMA overlay system, the ECC pavement system reduces energy consumption by 15% and 72%, GHG emissions by 32% and 37%, and costs by 40% and 58%, respectively.

In conclusion, material, traffic, and roughness effects are the greatest contributors to environmental impacts throughout the overlay system life cycle. User costs dominated total life cycle costs. The integrated LCA-LCCA model captures cumulative traffic flows, overlay deterioration over time, and maintenance activities to evaluate life cycle environmental burdens and costs.

2.1.7 Santero (2009)

Santero in his PhD dissertation (2009) studied the life-cycle global warming potential of pavements. The study covered all LCA phases: material, construction, use, maintenance and end of life phases. Various reported values from the literature were used to calculate GHG emission for the material phase. The author computed CO_2 factors for pavements and base per unit volume. The factors for flexible, rigid pavements, and aggregate base were 134 kg CO_2/m^3, 274 kg CO_2/m^3 and 5.6 kg CO_2/m^3, respectively. For the construction phase, Santero claimed that the placement phase of the life cycle was responsible for only a few percent of the total energy and CO_2 emission by referring to several reports.

Unlike previous studies, Santero emphasized the effect of the use phase. For the impact of traffic delays, the author estimated that the range CO_2 emission could be from 600 to 10,000 Mg. For carbonation, deteriorated concrete pavements can sequester up to 110 Mg of CO_2. The author highlighted the effect of rolling resistance as the single most influential factor on CO_2 emission. According to Santero, the CO_2 emission from rolling resistance could reach up to 91,000 Mg, which can be many times greater than all CO_2 emission combined from other LCA phases.

2.1.8 Eurobitume (2011)

Eurobitume (2011) inspected the LCI of asphalt binder. Unlike most of the other raw materials in pavement applications, binder must go through various allocation processes as it is just one product out of many other petroleum products obtained from crude oil. The ISO 14044 guidelines recommend the use of appropriate allocation procedures for such multi-product systems. Allocation refers to the distribution of energy and emissions to different products produced in one system. Allocation can be done based on mass, economic, and energy content of the products. In this study, mass allocation was used for crude oil extraction and oil transport, while economic allocation was used for the oil refinery process.

Inventory analysis was divided into four stages: crude oil extraction, oil transport, oil refining, and storage. For crude oil extraction, 17.5 kg of diesel and 5.2 kg of natural gas were used to extract one ton of crude oil. The primary sources of CO_2 were flaring and fuel burning for extraction. In the oil transport stage, depending on the geographic location, the method of transport differed. Crude oil from Russia is transported via pipeline, whereas oil from South America or Middle East is transported via tanker ship. Pipelines use 5.8 kWh of electricity per ton of crude oil transportation while ships use 7.2 kg of heavy fuel oil to transport one ton of crude oil. In the refining process, 98.3% of the energy used for crude oil refining is produced using refinery gas (79.2%) and heavy fuel oil (19.1%) while the remaining 1.7% is assumed to be electricity. In order to produce one ton of asphalt binder, 2.44 kg of heavy fuel oil, 8.18 kg of refinery gas, and 2.41 kWh of electricity are estimated through the economic allocation method. An additional 100 MJ of energy is used to store one ton of asphalt binder.

The study also separately includes inventory analyses for polymer modified bitumen and bitumen emulsion. Recommendations for moving from LCI to LCA and economic allocation at the refinery process are explained in the appendix of this study.

2.1.9 PaLATE (2011) and PE-2 (2011)

PaLATE is pavement LCA software developed by the University of California in 2003. This spreadsheet-based tool can estimate various emissions, energy use and water consumption in material, construction, maintenance, and end-of-life phases of a pavement. PaLATE uses a hybrid approach as it uses both EIO-LCA and process-based LCA. Despite these benefits, the tool faces two limitations. It uses an outdated database and does not consider the use phase. A new version of PaLATE was launched in 2011 by the University of Washington. Modifications made on the new version include the following:

- A more user friendly spreadsheet-based interface
- Compliance with Greenroads PR-3
- Removal of the life-cycle cost analysis
- Reduced outputs: only energy use and global warming potential (GWP)

Project Emission Estimator (PE-2) is web-based software that measures the amount of GHG from highway construction, rehabilitation and maintenance projects. The tool accounts for GHG emission for material, construction, use, and maintenance phases of a pavement. The tool uses a process-based approach as material and equipment inventories were collected from 14 pavement construction/maintenance projects and emission factors were collected from the literature and other databases. This convenient tool allows users to compare GHGs between various pavement and construction practices. However, the output of the tool is limited to GHGs; other important factors in the pavement use phase such as rolling resistance are not accounted for in the tool.

2.1.10 Wang et al. (2012) (UCPRC model)

Wang et al. (2012) investigated the energy use and GHG emissions in the material, construction, use and maintenance phases of flexible and rigid pavements. The LCA framework and model developed in this work was derived from guidelines proposed in the pavement LCA workshop (UCPRC, 2010). Pavement LCA guidelines recommends a comprehensive framework for conducting LCA for pavements and roadways. One of the main objectives of this study was to observe the difference in energy and GHG emissions between pavements with and without Caltrans Capital Preventive Maintenance (CAPM) treatments. These treatments were a spall and joint seal repair and the replacement of a fraction of slab for concrete pavements. The treatment for asphalt pavements was asphalt overlay. These treatments changed the roughness and texture of pavements and affected the energy use and GHG emissions between pavements and vehicles.

Wang et al. (2012) conducted four case studies: two for flexible pavements and the other two for rigid pavements. For each pavement type, one case represented a roadway with a low traffic volume and the other a high traffic volume. The study evaluated energy and emissions from all life-cycle stages of pavements. According to calculations after a certain time period, fuel and GHG emissions savings in the use phase can reconcile energy and GHG emissions from material production and construction. This *payback* time depends on the volume and growth rate of traffic as well as smoothness after construction. Wang et al. (2012) found that the most significant reduction in energy was related to the number of vehicles, followed by pavement maintenance, and then by changes in fuel economy of vehicles. By comparing the four case studies, the author concluded that pavement maintenance can contribute to a significant net reduction in energy use and GHG emission over the life-cycle of pavements. The author also argued that the net reduction in energy and GHG due to pavement maintenance can be equivalent to that from expected changes in vehicle fuel economy incorporated in MOVES.

2.2 Current Pavement Life-Cycle Assessment Studies

Based on the literature review of current pavement LCA studies, it should be noted that there are many different approaches used to conduct LCA. Most of the existing studies used process LCA, with Park et al. (2003) and PaLATE (2011) using hybrid LCA. The primary benefit of using process LCA is that results are more accurate, up-to-date, and reflect exactly what the researcher often seeks to analyze. However, process LCA is heavily dependent on the quality and quantity of data collected, making it a resource intensive LCA approach as compared to other LCA approaches. Despite the time and costs, the specificity achieved may explain why process LCA remains the dominant methodology.

Even if the same process LCA methodology is used, the results from various studies showed significant differences. For example, both studies by Stripple (2001) and the Athena Institute (2006) compared the flexible and rigid pavements in terms of energy use and CO_2 emission; however, they produced opposite results. Stripple (2001) showed that compared to flexible pavement, the energy use and CO_2 emission for rigid pavements in Sweden were 17% and 34% higher, respectively. However, the Athena Institute (2006) showed that compared to rigid pavements, the energy use and CO_2 emission for flexible pavements were 81% and 11% higher, respectively, for a section of Quebec freeway.

There are many factors that can affect the results of an LCA and are likely to explain discrepancies. Assumed system boundaries, inventory data validity, quality, geography, analysis duration and other assumptions may all contribute to the differences. It can also be speculated that since the states of economy, practice, regulation, and technology vary between Sweden and Canada, the fuel usage and emissions should also vary accordingly.

The source and quality of the data are also important factors that affect the result of LCA studies. The source of data can be directly collected and retrieved from commercial software or existing literature. Although it depends on the goal and scope of the study it is usually better to use directly collected and validated data to reflect regional proximity. However, it is nearly impossible to collect and validate all necessary data. Therefore, identifying and using reliable literature is crucial in filling in for missing data. For example, the Portland Cement Association (PCA) collected data on fuel and electricity at concrete plants from confidential LCI surveys for their PCC LCI study (PCA, 2007). However, the data on fuel and electricity to produce sand, gravel, and crushed coarse aggregates were retrieved from reports by the U.S. Census Bureau and the U.S. Geological Survey.

In the absence of any literature data, appropriate assumptions should be made as necessary. For example, Eurobitume (2011) made an assumption based on the size of ships that transport crude oil. The typical vessel size ranges from 130,000 to 250,000 Dead Weight Tonne (DWT) for the Middle East and 70,000 DWT for Europe but Eurobitume assumed the size to be 106,000 DWT for all regions.

Although the existing literatures provide a good reference for future pavement LCA studies there are still some limitations to be addressed. Not all pavement LCA studies include all of the LCA phases. As seen in Table 2.1, out of six pavement LCA studies (Stripple, 2001; Park et al, 2003; Athena Institute, 2006; Zhang et al., 2008; Santero, 2009; Wang et al., 2012), only two (Zhang et al., 2008; Santero, 2009) include all LCA phases. There is only one study (Santero, 2009) that includes a sensitivity analysis on the pavement life span. Santero compares the global warming potential from three various life-spans. Only one study (Eurobitume, 2011) incorporates emissions to soil, water and air. Including as many emissions as possible will help to extensively analyze environmental impacts in the life-cycle impact analysis stage. Two studies (Santero, 2009; Wang et al., 2012) show that the impact of rolling resistance on GHG emissions can be greater than any other pavement LCA phases or all other phases combined, emphasizing the importance of the use phase.

Some of the reported values in the literature are presented in Chapter 4 to check the quality of regionally collected data. Although many of the reported values are based on national averages, comparison between reported values and collected data is presented to check the reasonableness of the collected data.

Table 2.1 Summary of existing pavement related LCA

Author (year)	Title	Method	Period	Location	Outputs	LCA phase(s)
Stripple (2001)	Life cycle assessment of road: a pilot study for inventory analysis	Process	40 years	Sweden	Energy, air emissions	Material, Construction, Use, Maintenance
Park et al. (2003)	Quantitative assessment of environmental impacts on life cycle of highways	Hybrid	20 years	South Korea	Energy, air emissions	Material, Construction, Maintenance, End-of-life
Athena Institute (2006)	A life cycle perspective on concrete and asphalt roadways: embodied primary energy and global warming potential	Process	50 years	Canada	Energy, GHG emissions	Material, maintenance
PCA (2006)	Life cycle inventory of Portland Cement manufacture	Process	N/A	U.S.A.	Energy, air emissions	Material
PCA (2007)	Life cycle inventory of Portland Cement concrete	Process	N/A	U.S.A.	Energy, air emissions	Material
Zhang et al. (2008)	An integrated life cycle assessment and life cycle analysis model for pavement overlay system	Process	20 years	U.S.A.	Energy, GHG emissions	Material, Construction, Use, Maintenance, End-of-life
Santero (2009)	Pavements and the environment: a life-cycle assessment approach	Process	20, 40, 100 years	U.S.A.	Energy, air emissions	Material, Construction, Use, Maintenance, End-of-life
Eurobitume (2011)	Life cycle inventory: bitumen	Process	N/A	Belgium	Energy, emissions to soil, water and air	Material
PaLATE v2.2 (2011)	The Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (Software)	Hybrid	N/A	U.S.A	Energy, GHG emissions	Material, Construction, Maintenance, End-of-life
PE-2 (2011)	Project Emission Estimator (Software)	Process	N/A	U.S.A	GHG emissions	Material, Construction, Use, Maintenance
Wang et al. (2012)	UCPRC Life Cycle Assessment Methodology and Initial Case Studies on Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance	Process	5 years for flexible, 10 years for rigid pavements	U.S.A	Energy, air emissions	Material, Construction, Use, Maintenance

CHAPTER 3. GOAL AND SCOPE DEFINITION OF LIFE-CYCLE ASSESSMENT

According to ISO 14044 (2006), there are four phases in the development of an LCA: goal and scope definition, inventory analysis, impact assessment and interpretation. This chapter covers goal and scope definition of the pavement LCA developed in this study.

3.1 Goal of the Pavement Life-Cycle Assessment

The intended application is to measure the sustainability of pavements by investigating the energy consumption and emissions from the processing and transporting of raw materials. This study presents the preliminary version of a LCI database that will eventually be used in the LCA tool being developed by the University of Illinois at Urbana-Champaign for the Illinois Tollway. Therefore, the LCA tool is anticipated to reflect the local aspect of the upper Illinois region, as the locally collected data are incorporated in the inventory database. This study will contribute to the development of inventory database, an important part of a complete pavement LCA study.

The targeted audience consists of governmental organizations, academic researchers, pavement consulting firms, and pavement material manufacturers interested in environmental issues regarding pavements. The results of the study will be disclosed to the public for a comparative study; however, the inventory database itself will remain closed to the public due to manufacture confidentiality. Users should be aware that the results of using the regional inventory database are representative of upper Illinois area to a certain extent.

3.2 Scope of the Pavement Life-Cycle Assessment

A comprehensive LCA should include all the steps in the life-cycle of a product from upstream processes such as raw material acquisition to a consumed product's destruction. However, the scope of this study is limited to material acquisition and production stage.

In most LCA studies, the influence of building and maintaining fixed capital is neglected but the operation of fixed capital is considered. For example, the construction of material production plants such as hot mix asphalt (HMA) plants, cement plants, and ready mix concrete plants are not considered but the energy use and emissions from operating these plants are measured. Similarly, the environmental impact from manufacturing vehicles is neglected but the operation of these vehicles such as fuel consumption is considered in the LCA study.

3.2.1 Pavement structure

Typical pavement LCA considers all layers existing in flexible and rigid pavements as follows:

- Wearing surface: a smooth riding surface layer usually made of asphalt concrete in contact with traffic loads that provides skid resistance for vehicles and good drainage to protect underlying pavement layers
- Binder layer or base course: a layer beneath the wearing surface usually consists of bound (binder layer) or unbound/stabilized crushed rock that provides a foundation to support the surface layer
- Subbase course: a layer beneath the binder layer/ base course usually consists of unbound granular materials that provides a structural support and protects the subgrade
- Subgrade: Natural or stabilized soil underneath the subbase course that works as a platform for the pavement system.

This study considers the pavement layer above the aggregate base layer. Future work will be expanded to consider all other pavement layers and pavement shoulders. The schematic of a typical pavement structure is illustrated in Figure 3.1.

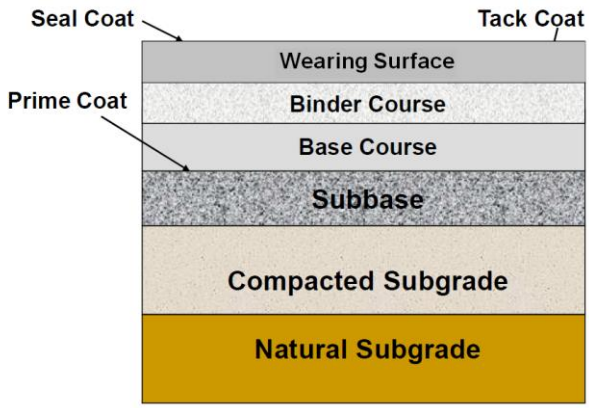


Figure 3.1 Conventional flexible pavement (after Al-Qadi, 2012)

3.2.2 Functional unit

The functional unit is a reference to which the input and output data are normalized (ISO, 2006). Depending on the materials, the typical functional unit varies. The functional unit for raw materials is usually a unit mass or volume. For example, in the asphalt binder LCI study done by Eurobitume (2011) the functional unit is a ton of asphalt binder, while in the PCC LCI study (PCA, 2007), it is a cubic yard of concrete. Life-cycle assessment studies define the functional unit to be a section of pavement that is simple, yet meaningful unit representing pavement construction (Stripple, 2001; Park et al, 2003; Athena

Institute, 2006; Zhang et al., 2008; Santero, 2009). Unlike the functional unit for material LCI studies, the functional unit for pavement LCA studies is a bit more complex because performance characteristics need to be considered. For example, the amount of raw materials needed to construct one lane-mile of an Interstate highway is much larger than that needed to construct one lane-mile of a local road. In other words, the energy use and emissions associated with one lane-mile of an Interstate highway will be much greater than those associated with one lane-mile of a local road. Depending on the annual average daily traffic (AADT), type of road varies, and as do pavement designs. Hence, when comparisons between pavement systems are made, the systems should have the equivalent performance to avoid an erroneous comparison.

3.2.3 System boundaries

The system boundaries identify what is included and what is excluded in the life-cycle of a product. Depending on how the system boundaries are drawn, the result of an LCA can change significantly. As introduced in Chapter 1, the LCA has five phases: material, construction, use, maintenance, and end-of-life (EOL). In this study, only the material phase is covered. Hence, the system boundary for the material phase is illustrated in Figure 3.2.

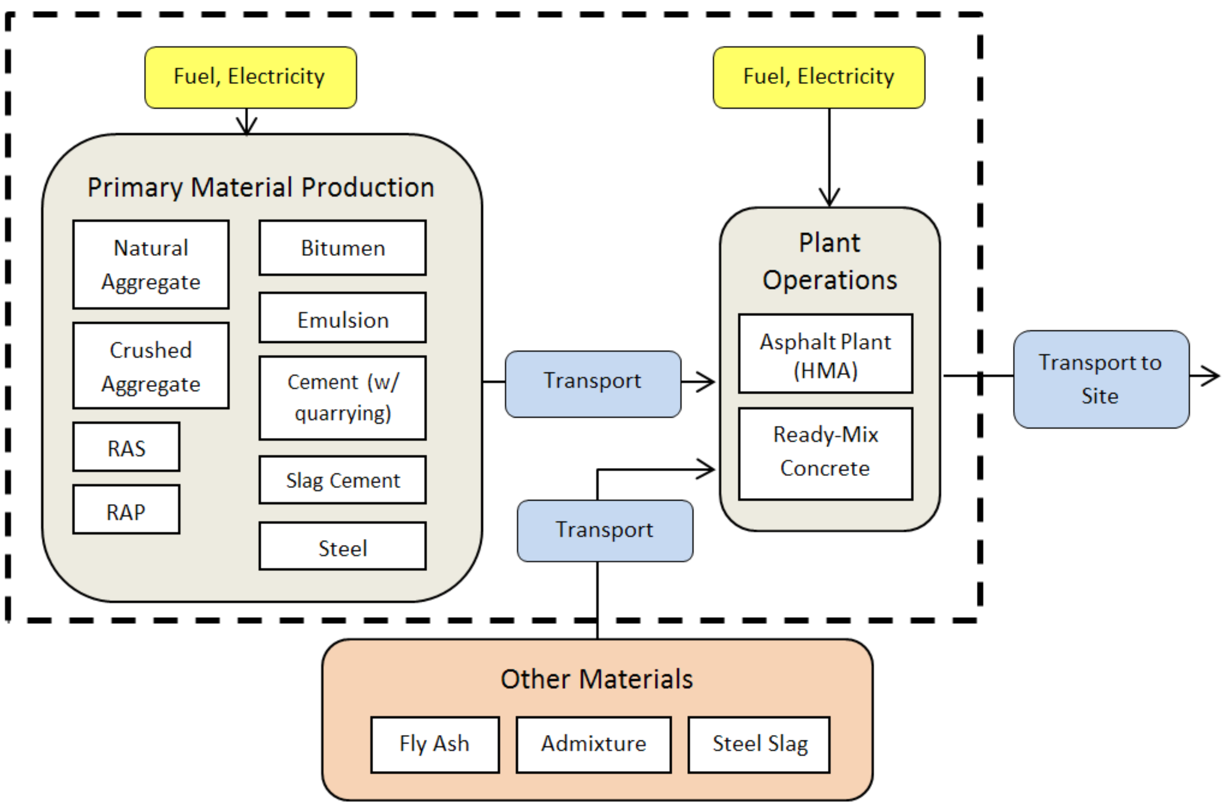


Figure 3.2 The system boundary for the material phase

The flow of pavement material production can be traced as seen in Figure 3.2. Primary materials including aggregates, asphalt binder, emulsion, cement, slag cement, steel, recycled asphalt shingle (RAS), and reclaimed asphalt pavement (RAP) and other materials including admixture, fly ash, and steel slag are transported to hot mix asphalt (HMA) plants and/or ready mix concrete plants to produce various types of pavement mixes. The finished mixes are transported to construction sites.

The materials and activities within the dashed rectangle are included in the system boundary of the material phase. In other words, the material phase only includes the LCI of primary pavement materials such as aggregates, asphalt binder, cement and plant operations used to produce HMA and PCC. Admixture is not included in the material phase due to data availability but will be included in future studies. The productions of fly ash and steel slag are not considered because the materials are assumed to be industrial wastes from coal combustion and steel production, respectively. The only contribution of these materials to the inventory database is transporting them to the mixing plants.

For some of the primary materials, an allocation process is needed. For example, asphalt binder is not the only material produced from crude oil: there are also other co-products such as gasoline and diesel. Hence, the need for allocation is inevitable. The study primarily refers to Eurobitume (2011) for asphalt binder production LCI. Therefore, a mass allocation is used for crude oil extraction and transportation and an economic allocation is used for crude oil refining. It is also important to consider the energy used to produce fuels and electricity.

3.2.4 Data collection and quality

Regarding data quality, both reported values from the literature and collected data should be checked. Also, more recent data with geographical proximity to the U.S. and the Midwest are prioritized and used preferentially. For collected data, 6-12 months of data were requested to check seasonal variations and the values were cross-checked with literatures. Most of the collected data are from the Illinois area for geographical proximity. The values between the collected data are also compared and if any significant difference is found between collected data, follow up communication is made to verify the data quality.

There are certain inventory items to be collected in the study. The categories of inventory items include primary energy used, water consumption, greenhouse gases (GHGs), air and water pollutants, and solid wastes. Details of the inventory items are listed in Table 3.1.

Table 3.1 The list of included life-cycle inventory items

Categories	Inventory items
Primary energy used	Electricity, coal, petroleum coke, gasoline, diesel, natural gas, residual oil, etc.
Water consumption	The amount of fresh water used
Greenhouse gases	CO_2, CH_4, N_2O
Air pollutants	PM 2.5, PM 10, CO, NO_x, SO_2, VOC, etc.
Water pollutants	Chemicals or heavy metals
Solid wastes	Dust, by-products, etc.

3.3 Major Assumptions Adopted in the Development of Life-Cycle Assessment

It is important to clearly state any assumption made in an LCA to avoid confusion and controversy. The following section discusses the direct and indirect fuel/electricity uses and the corresponding assumptions made.

3.3.1 Energy and emissions associated with direct fuel/electricity use

The U.S. Energy Information Administration (EIA) defines direct emission as the emissions from sources within the organizational boundaries of an entity (U.S. DOE, n.d.). It includes emissions that result from both stationary and mobile sources' combustion (U.S. EPA, 2008). Direct energy refers to the energy obtained during fuel combustion or electricity. Pavement surface materials such as asphalt mixes and PCC are produced in plants where raw materials and energy sources are transported from outside. Energy consumption and emissions due to fuels and electricity used in plant operations and transportation of raw materials constitute direct energy usage and corresponding emissions.

The data for energy and emission due to plant process operations including cement production, aggregate crushing, HMA production, and others are obtained from questionnaire responses or literatures. On the other hand, direct emissions due to operating mobile sources such as dump trucks and loaders are initially calculated based on the emission factors from EPA's Mobile Combustion Source (U.S. EPA, 2008). However, it was found that EPA's recent emission estimation model is assumed to simulate a more reliable result so this model will replace the old emission factors. The GHG emission factors for barges and construction equipment are used to analyze the material transportation data in collected questionnaires. Table 3.2 shows the energy and emissions for direct fuel use.

Table 3.2 Direct emissions for various fuels for construction equipment (after U.S. EPA, 2008)

	Unit per gal	Gasoline	Diesel
N_2O	lb	0.000485	0.000573
CH_4	lb	0.00110	0.00128
CO_2	lb	19.4	22.4

3.3.2 Energy and emissions associated with indirect fuel/electricity use

Energy is also required to produce fuels and electricity in the downstream processes. Therefore, in addition to the energy use and emission of direct use of fuels and electricity, the energy and emissions associated with the production of these fuels and electricity are also considered. For simplicity, these energy and emissions will be referred to as *indirect energy and emissions*. Calculating indirect energy and emissions is more complex than calculating direct energy and emissions. In order to compute indirect energy and emissions, *GREET* by Argonne National Laboratory (GREET, 2012) and *eGRID* by EPA (U.S. eGRID, 2012) are used.

GREET is an open spreadsheet-based software used to evaluate the impact of fuel use in transportation. The model incorporates the fuel cycle from well to wheels. In other words, the GREET model includes all fuel production processes from oil exploration to fuel use by vehicles. Since the purpose of using the GREET model is to find the indirect energy and emissions for fuels, we focus on the calculation process of energy consumption and emissions for petroleum fuels by stage. For example, when we want to calculate the energy and emissions for conventional gasoline, energy consumption and emissions are included from the process of crude oil extraction, transportation, refinery and transportation to the user.

The indirect energy and emissions are retrieved from GREET's database for conventional diesel, gasoline, liquefied petroleum gas, residual oil, coal and petroleum coke because these petroleum fuels are often used for plant power generation and transportation. GREET provides the process energy per unit primary energy or the indirect energy needed to produce one unit of the desired energy from a fuel. In order to calculate the process energy (btu/Mbtu), it is multiplied by primary energy (in Mbtu) per gallon of fuel.

The study assumes that fuels have the lower heating value (LHV) for primary energy and that 8% of the crude oil is derived from oil sands throughout the calculation. The amount of various emissions associated with the process energy usage is also calculated in a similar fashion as explained above. These emissions include volatile organic compound (VOC), carbon monoxide (CO), nitrogen oxide (NO_x), particulate matters ($PM_{2.5}$ and PM_{10}), sulfur oxide (SO_x), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). The results of indirect energy and emissions calculation for various fuels based on GREET are summarized in Appendix A.

For the process energy of electricity, eGRID is used to obtain data from Illinois' electricity grid. To calculate the energy required to produce 1 kWh of electricity, the annual net generation (in kWh) and annual heat input (in Mbtu) of Illinois' total electricity generation are used. The process energy (Mbtu/kWh) is computed by dividing the annual net generation by the annual heat input. Similarly for emissions, various annual emissions (in tons) are divided by the state annual net generation of each plant (in kWh). The result is the emission (in ton) per generation of 1 kWh of electricity. eGRID not only has emission information on GHGs but also information on other emissions such as NO_x, SO_2, and mercury (Hg). It is assumed that the relevant eGRID sub-region names representing Illinois' electricity grid are SERC Midwest, RFC West, and MRO West. The results of indirect energy and emissions calculation for electricity based on eGRID are summarized in Appendix A.

CHAPTER 4. LIFE-CYCLE INVENTORY ANALYSIS

Life-cycle inventory analysis is the second step in the LCA as defined in ISO 14044 (ISO, 2006). Based on the goal and scope of the LCA developed in this thesis, data collection and data calculation were carried out. This chapter summarizes the data collection process and presents the data collected from different sources. Typical input deduced from the regional and literature sources were energy and emissions to air, water and soil.

4.1 Life-Cycle Inventory Items

The environmental indicators of a product include energy used (fuel and electricity), greenhouse gases (GHGs), and some other major emissions as in Table 3.1. It will be advantageous to collect as much emissions data as possible for a more detailed impact assessment in the future study. Although various emission inventory items were collected in the database, not all of them will be used because only a partial impact assessment will be performed in the thesis. A further discussion of life-cycle impact assessment will be provided in the following section.

4.2 Data Collection from Regional Sources

A set of questionnaires, consisting of a confidential life-cycle inventory survey, were distributed to various plants and contractors to collect inventory data specific to Illinois. The questionnaires consisted of two main parts: general questions and plant operations. For some of plants, a more detailed questionnaire was prepared in order to investigate multiple products from one plant and to assess plant efficiencies. An example questionnaire is shown in Appendix B for reference.

The following are typical questions to collect general information about plants:

- Reporting period
- Technical aspects of plants
- Plant operation process
- Amount of production during the reporting period and daily production
- Representative mix designs (for HMA and ready mix concrete plants)
- Dust control method
- Seasonal energy use
- Any special treatment made during material production

The second part of the questionnaire was designed to collect data for energy use and emission at each production stage. Areas of interest include the following:

- Raw/recycled material transportation from its original location to processing units
- Operation of in-plant transportation equipment
- Electricity, fossil fuels, water usage at each production stage per ton of product
- Emissions to air, water, and soil per ton of product.

A total of seven questionnaires were prepared and distributed to local material production plants. The following list shows the types of material production plants that responded to the surveys:

- Crushed and natural aggregate production
- Asphalt binder production plant
- HMA production plant
- PCC production plant
- Ready mix concrete production plant
- Recycled materials such as RAP, RAS, recycled concrete aggregate (RCA) production
- Supplementary cementitious material (cement slag, fly ash)

Once the data were collected from the plants, the values were analyzed and compared with the reported values in the literatures. If collected data were much larger or smaller than these values, it was necessary to pursue follow-up communications with data providers to determine the source of the discrepancy. The discussion on the inventory analysis was covered in depth in the following section. Table 4.1 shows the result of questionnaire distribution to plants.

Table 4.1 The number of questionnaires returned

Material(s)	**# of returned questionnaire**
Crushed and natural aggregate production	2
Asphalt binder production	2: Blending 1: Emulsion
HMA production	3
Cement production	1
Ready mix concrete production	2
Recycled materials (RAP, RAS, RCA) production	4: RAP 1: RAS 1: RCA
Supplementary cementitious materials	1: Slag cement

As seen in Table 4.1, there were only a limited number of questionnaires responses collected from plants. In general, only one or a few questionnaire responses were collected for each type of plants. This was not sufficient to observe the variance in the collected data; therefore, it was necessary to collect additional data from each plant. In the study, a table was presented for each plant to compare the collected data to literature values. If a sufficient number of questionnaires are collected from each plant, a statistical analysis should be performed on collected data and literature values.

4.2.1 Aggregate production

There are three types of aggregate production considered in the LCI: crushed coarse aggregate, natural fine aggregate and crushed fine aggregate. A separate questionnaire was prepared and distributed to each source of aggregate. Typically, natural aggregate is dredged from sand and gravel pits whereas crushed aggregate is quarried and crushed with operations and equipment different from that of natural aggregate production. The general information obtained from two responses is summarized in Table 4.2.

Table 4.2 Summary of collected aggregate questionnaires

	Plant 1	**Plant 2**
Type of Plant	Sand/Gravel Pit	Unknown
Reporting Period	01/01/2012 – 08/30/2012	01/01/2012 – 08/30/2012
Production	109,745 tons	71,700 tons
Other Notes	Plant 1 produced CA-6, CA-11, and CA-16. 100% of fines from crushing go into crushed products. No water is pumped	Plant 2 produced FM-2.

Both responses described their plants as dredge operations, and the energy use for both plants was the same. This implies that the energy use for crushing was not included. The energy values obtained from questionnaires were quite different from the literature. Table 4.3 indicates that the differences in reported electricity usage between questionnaire responses and literatures was not high but that the energy from fuel use was many times greater in the survey responses than that in the literature. In addition, the collected data for aggregates constitute only a small portion of total aggregate use in the production of HMA and PCC. Since regional data was collected only from a few aggregate producers, the literature values were used for the aggregate inventory.

Table 4.3 Comparison of energy usage between questionnaire responses and literatures

Energy type	Units	Plant 1	Plant 2	PCA, 2007	PCA, 2007
--	--	CA-6, 11, 16	FM-2	Sand & gravel	Crushed sand and gravel
Diesel (from loaders)	Gal	0.62	0.62	0.069	0.108
Energy (from diesel)	Btu*	86,000	86,000	9,681	15,087
Electricity (from dredging)	kWh	4.90	4.90	2.41	2.96
Energy (from electricity)	Btu	16,700	16,700	8,210	10,088
Total Energy	Btu	103,000	103,000	20,000	30,500

Conversion: 1 Btu = 1.06 kJ

* Btu = British thermal unit

4.2.2 Asphalt binder and emulsion

Two questionnaire responses were collected for asphalt binder and emulsion. The first questionnaire contained data on binder blending and the second contained data on asphalt emulsion storage. Even though the type of binder produced at each plant was different, the production stages of two plants were similar as shown below. Table 4.4 shows the summary of questionnaire responses.

- Procurement of raw materials such as binder and emulsifier
- Storage of raw materials in heated storage tanks
- Blending of product
- Storage of finished product in tanks
- Loading to tanker trucks

Table 4.4 Summary of asphalt binder questionnaires

	Plant 1	Plant 2
Type of plant	Asphalt blending	Asphalt emulsion storage
Reporting period	10/2011 – 10/2012	11/2011 – 11/2012
Production	18,000 tons	20,000 tons
Other notes	Produced: PG58-28 (39%), PG70-28SBS (50%), PG70-28GTR (11%)	Produced: Emulsion (100%)

The system boundary of asphalt binder typically consists of four primary production stages: crude oil extraction, transportation, crude oil refining, and storage as shown graphically in Figure 4.1. The flow diagram is broken down into more detail stages but it essentially summarizes the four primary production stages mentioned above. Since the responses only covered the very last stage of asphalt binder and emulsion production, neither of the two responses contained information on crude oil extraction, transportation, and crude oil extraction. Due to insufficient data, data from Eurobitume (2011) were used to analyze the inventory of asphalt binder and emulsion.

The study by Eurobitume (2011) investigated the life-cycle of three binder types: straight binder, polymer modified binder (PMB), and emulsified binder. The literature listed energy use and emission information separately for each binder production stage. The limitation of the literature comes from the location of the study. Since there is a discrepancy between the U.S. and Europe the inventory data may not reflect the exact condition of the U.S. case. However, the report provides the most appropriate data that is publicly available for the purpose of completing the current stage of the study. In addition, the comprehensive analysis of the LCI of the three binder types is anticipated to be beneficial to build an initial LCI database. In order to check the data from the study by Eurobitume (2011), other available data from Athena Institute (2001) and Stripple (2001) were used. The energy use and GHGs were compared among these literatures and the result is summarized in Table 4.5.

Table 4.5 Summary of comparison among binder questionnaire responses and literatures

	Unit per ton of binder	Plant 1	Plant 2	Athena Inst. (2001)	Stripple (2001)	Eurobitume (2011)
CO_2	ton	1.01×10^{-7}	0.0256	0.204	0.173	0.174
N_2O	ton	N/A	N/A	3.58×10^{-4}	1.06×10^{-7}	N/A
CH_4	ton	N/A	N/A	0.836	3.53×10^{-8}	5.95×10^{-4}
CO_2EQ	ton	1.01×10^{-7}	0.0256	21.2	0.173	0.189
Energy	Btu	8.25×10^{4}	4.30×10^{5}	2.66×10^{6}	3.27×10^{6}	2.65×10^{6}
Notes	---	No crude oil extraction or refining	No crude oil extraction or refining	CO_2EQ large because of large CH_4		Straight binder

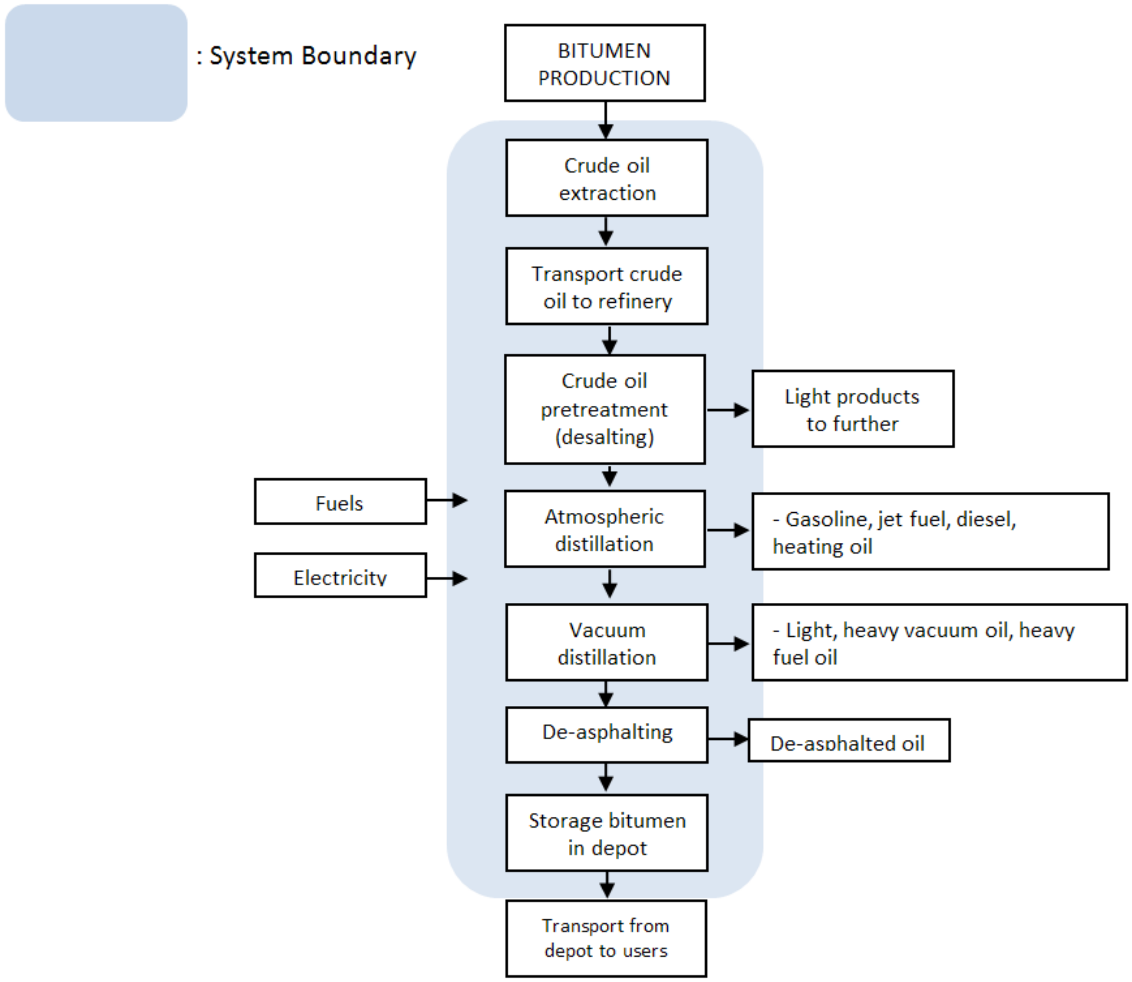


Figure 4.1 The flow diagram of asphalt binder production (after Stripple, 2001)

As in Table 4.5, the values of energy use are much smaller at both plants than the literature suggests. This was expected as questionnaire responses did not include some of the primary production stages. However, the energy values for three previous studies are similar, implying that the Eurobitume (2011) data agree well with the data reported elsewhere. For GHGs, plants have much lower emissions than literature values for the same reason. Since the CH_4 emissions in the study by Athena Institute (2001) were much higher than the other literature values the CO_2 equivalent was also much higher.

In the case when several different products are produced simultaneously, the energy use and emission should be allocated between these products. There are multi outputs produced from the crude oil refining process such as gasoline, kerosene, diesel, and asphalt. Thus, all of these products are responsible for the total energy and emission. However, only the contribution of asphalt binder production is of interest herein.

In Stripple (2001), 40% of the mass of crude oil is assumed to be allocated for asphalt binder and the remaining 60% of mass for other lighter products. In Eurobitume (2011), both economic and mass allocations were used. The asphalt binder yield from crude oil was 22.3% by mass and the economic allocation coefficients for crude oil distillation unit (CDU) and vacuum distillation unit (VDU) were 0.31 and 0.27, respectively. Eurobitume (2011) computed the energy for asphalt binder production using this information and a sensitivity analysis on different types of allocation methods was performed. Since the information on crude oil extraction and refining was missing in questionnaire responses, the inventory data on binder production by Eurobitume (2011) was used for developing our LCI database.

4.2.3 Hot mix asphalt (HMA) plant

Aggregates, asphalt binder, and other raw materials are all brought to a plant that produces HMA. Aggregate and asphalt binder production were investigated in the previous sections so this section explored environmental burdens of HMA production. As for data collection, three questionnaire responses were collected and all three HMA plants were reported to be drum-mix type plants. The types of binder used during the production were PG76-22, PG58-28, PG70-28, and PG64-22 at all three plants. The general information on three HMA plants is summarized in Table 4.6.

Table 4.6 Summary of HMA plant questionnaires

	Plant 1	**Plant 2**	**Plant 3**
Plant type	Drum	Drum	Drum
Reporting period	05/2012 – 09/2012	07/2012 – 09/2012	07/2012 – 09/2012
Production	334,450 tons (2,779 tons /day)	131,000 tons (1,500 tons/day)	57,342 tons (700 tons/day)
Mix designs	WMA N80 SMA Surface WMA N80 SMA F Surface WMA N50 Binder WMA N70 Surface HMA N90 F Surface WMA N80 SMA Binder	N50 D Surface 81BIT409A N70 D Surface 81BIT417A N70 D Surface 81BIT421A N90 F Surface 81BIT444A N30 BAM 2% 81BIT436A N50 Poly level Binder 81BIT416A N50 Binder 81BIT 414A N70 Binder 81BIT415A	N50 D Surface 81BIT422A N50 D Surface 81BIT424A N70 D Surface 81BIT423A N70 Binder 81BIT 425A N90 D Surface 90BIT1215 N90 Binder 81BIT441A N70 D Surface 90WMA1224 N50 Binder 90WMA1223

Because road construction usually takes place during the warmer seasons the reporting period of each plant lies between May and September. The daily production rate of Plant 1 is about twice that of Plant 2 whose production rate is in turn twice that of Plant 3. Each plant produced various mix designs including conventional HMA and warm mix asphalt (WMA) using different types of asphalt binder. Table 4.7 shows the boiler temperatures for various types of binder and Table 4.8 shows various storage temperatures for different mix designs.

Table 4.7 Boiler temperatures for different types of binder

	Binder boiler temperatures (°F)			
	PG 76-22	**PG58-28**	**PG70-28**	**PG64-22**
Plant 1	325 (315-330)	300 (280-305)	325 (295-320)	300 (285-315)
Plant 2	325 (315-330)	325 (280-305)	325 (295-320)	300 (285-315)
Plant 3	340 (315-330)	325 (280-305)	340 (295-320)	N/A

Depending on the binder types being held, the storage temperature varies. The ranges shown in parentheses in Table 4.7 are typical asphalt binder storage temperatures advised by Asphalt Paving Environmental Council (APEC, 2007). Plants 1 and 2 seemed to be in accordance with the guideline temperature but Plant 3 generally had a higher storage temperature for each type of binder than the guidelines suggest. According to APEC (2007), the mixing temperature for each type of binder seemed generally 10 °F lower than the storage temperature.

Table 4.8 Asphalt mixture storage temperatures

	Asphalt mixture storage temperatures (°F)				
	Average HMA	**WMA**	**Polymer HMA**	**State mix**	**Private mixes (small handwork)**
Plant 1	300 °F	265 °F	350 °F	N/A	N/A
Plant 2	N/A	290 °F	N/A	325 °F	350+ °F
Plant 3	N/A	290 °F	N/A	325 °F	350+ °F

Depending on the binder type, the storage temperature for asphalt mixtures also varied. As shown in Table 4.8, the storage temperature was higher for polymer HMA and private mixes than for average HMA and WMA. Since WMA allows for a reduction in temperatures during mixing and placing it is anticipated to provide potential advantages such as energy savings and emission reduction. The contribution of WMA to pavement sustainability is important but at this stage the study will not analyze the effect of WMA on environment.

Questionnaire responses also contained information on the handling of RAP and RAS. Plants 2 and 3 protected the RAP and RAS stockpiles from airborne erosion and moisture. Plant 1 reported that the virgin aggregates were superheated during the production of conventional HMA using recycled materials. However, the aggregates are not superheated during the production of WMA. The following list represents the commonly shared asphalt mixture production stages among all three plants:

- Transporting raw materials (binder, aggregate, fillers, etc.) to plants by trucks
- Stockpiling raw or recycled material and storing binders in the heated tanks
- Crushing and screening recycled materials (RAS and RAP)
- Feeding raw and recycled materials into the mixing drum for asphalt mixture production
- Transporting from drum to silos

Natural gas and electricity were the main sources of energy used to produce asphalt mixes at all three plants. The total energy usage to produce one ton of asphalt mixture is shown in Table 4.9 along with the energy values from the literature. The energy value in Plant 1 agreed well with literature values but Plants 2 and 3 gave values that differed significantly from the literature. As a result of a follow-up communication with plant 3, it was found that plant 3 is a retail type of plant that relies heavily on natural gas. In addition, plant 3 makes frequent starts and stops, thus consuming more energy to reheat its facility for production than plants operating full-time. Hence, the data from plant 3 was considered to be an outlier and was not included in the final LCI database.

Table 4.9 Comparing the energy values from questionnaires to HMA literatures

	Unit	Plant 1	Plant 2	Plant 3	U.S. EPA, 2004	Stripple, 2001	Zapata et al., 2005
Electricity	Mbtu*	0.0068	0.0301	0.00567	N/A	0.031	N/A
Natural gas	Mbtu*	0.270	0.894	2.428	N/A	0.00029	N/A
Total	Mbtu*	0.278	0.898	2.433	N/A	0.345	0.305

* Energy values are based on per ton of HMA production.

Table 4.10 compares the GHG values from questionnaires and the literature. CO_2 emissions from both are comparable because they are all in the same order of magnitude. Stripple (2001) reported a significantly lower CH_4 emission than others, while plant 1 had a much larger N_2O emission than the other. Combining all GHGs, the CO_2 EQ. was calculated for each plant and study. However, since the contribution of CH_4 and N_2O to CO_2 EQ. was insignificant compared to that of CO_2, the values of CO_2 EQ seemed to be comparable for each case. In other words, values obtained from the responses were acceptable. As such, similar to the energy, the averages of Plants 1 and 2 were used for the LCI database.

Table 4.10 Comparing the GHG values from questionnaires to HMA literatures

	Unit	Plant 1	Plant 2	Plant 3	U.S. EPA, 2004	Stripple, 2001	Zapata et al., 2005
CO_2	Ton*	0.0335	0.0182	0.0369	0.0165	0.0226	N/A
CH_4	Ton*	5.97×10^{-7}	6.01×10^{-6}	5.00×10^{-6}	6.00×10^{-6}	5.04×10^{-9}	N/A
N_2O	Ton*	3.12×10^{-7}	3.65×10^{-9}	6.66×10^{-9}	N/A	1.51×10^{-8}	N/A
CO_2 eq.	Ton*	0.0337	0.02	0.0384	0.0167	0.0226	N/A

* Mass values are based on per ton of HMA production.

4.2.4 Cement production

The production of cement is a very energy intensive, and hence a large CO_2 emitting process. In addition, the production of cement also involves the calcination of clinker, which results in significant CO_2 emissions. Thus, it is important to investigate the life-cycle inventory of cement production in pavement LCA. In order to estimate the energy consumption and emission for cement production a returned questionnaire response was analyzed along with a study by PCA (2007). The following represent the major stages of cement production provided in the response:

- Preparing raw materials (limestone crushing/pre-blending)
- Preparing raw meal (raw mill feed and raw mills)
- Producing clinker (kiln feed, kiln dust, pyro processing, clinker transport and storage)
- Finish grinding (cement mills)
- Packaging and shipping

Table 4.11 Summary of a cement questionnaire response

	Plant 1
Plant type	Dry preheater/precalciner cement plant
Reporting period	01/01/2012 – 12/31/2012
Production	4,043,553 tons
Notes	Produces Type-I and II cement Does not produce Type III cement

As shown in Table 4.11, Plant 1 is a preheater/precalciner cement plant — the most efficient type of cement plant. Plant 1 produced both Type-I and II cement but the questionnaire response is based on Type-I cement production. Future studies will collect data on Type-III cement so that a comparison can be made between types of cement produced.

Table 4.12 compares the energy use and GHG emissions between the questionnaire response and the literature. Both plant 1 and other studies used various types of fuel and electricity. Since Plant 1 is a preheater/precalciner cement plant, the data for the precalciner plant was used from the literature for comparison. The energy consumption in Plant 1 was about 7 % greater than in the literature, but the CO_2 emission was about 22% less. The energy values seemed to agree well with the literature, so they were also included in the final LCI database. Even though the difference in CO_2 emission was higher than that in energy use, it was still used in the LCI database because the questionnaire response was assumed to better reflect the regional data. However, the amount of CO_2 emission needs to be broken down into stages so further data collection is necessary to improve the current LCI database.

Table 4.12 Comparison of energy and GHG emission between questionnaire and literature

Resources	Unit per ton of cement	Plant 1	PCA, 2006
Electricity (for grinding operation)	Mbtu	0.0983	0.403
Electricity (for all other operations)	Mbtu	0.179	N/A
Gasoline	Mbtu	0.000675	0.00263
Middle distillates	Mbtu	0.0308	0.0410
Coal	Mbtu	2.15	2.07
Petroleum coke	Mbtu	0.810	0.367
Wastes (oil)	Mbtu	0.0167	0.187
Other fuels	Mbtu	N/A	0.00200
Total energy	Mbtu	3.29	3.07
CO_2 emissions	Ton	0.682	0.875

4.2.5 Ready mix concrete plant

Two questionnaire responses were collected for ready mix concrete production. Plant 1 produced three mix designs by changing the water to cement (w/c) ratio and the amount of aggregate. Plant 2 produced two mix designs by changing the amount of cement, fly ash, and admixtures. General information on Plants 1 and 2 is presented in Table 4.13. The typical ready mix concrete production stages are shown as follows:

- Transporting raw materials (aggregate, cement, water, admixtures, etc.) to plant
- Stockpiling at plant site or storing in tanks
- Feeding materials into the mixer
- Transferring the final mix to concrete mixer trucks

Table 4.13 Summary of ready mix concrete questionnaires

		Plant 1			**Plant 2**		
Plant type		Ready mix			Ready mix		
Reporting period		6/2012 – 12/2012			06/2007 – 09/2007		
Production		53,600 yd^3			34,000 yd^3		
Mix information	Mix design #	Volume (yd^3)	28-day strength (psi)	Unit weight (lb/ft^3)	Volume (yd^3)	28-day strength (psi)	Unit weight (lb/ft^3)
	1	40,700	4,300	3,872	30,000	N/A	N/A
	2	5,800	4,000	3,888	4,000	N/A	N/A
	3	7,100	4,400	3,868	N/A	N/A	N/A

Fly ash was the only supplementary cementitious material used in both plants. The production of fly ash was not considered in the study because it was assumed to be an industrial by-product, though, the transportation of fly ash was considered. The primary fuels used were residual oil and distillate fuel oil for Plants 1 and 2, respectively. The fuels were used in generators to supply power to plants. For recycling, Plant 1 used the majority of returned concrete to produce concrete blocks with dimensions of 4’x4’x4’ and 4’x2’x3’ and the remainder was crushed and used as base layer materials. Plant 2 crushed 95% of returned concrete to produce CA-6 and the remainder was discarded.

The energy usage in the two plants and two reports are summarized in Table 4.14. It is noted that questionnaire responses have higher energy values than the literature reports. In particular, the energy value for Plant 2 is about 21 times greater and 8 times greater than the study by Zapata et al. (2005) and PCA (2007), respectively. Due to the large discrepancy between questionnaires and literatures, it was assumed that literature values were more realistic and reliable at this stage. Therefore, in order to reflect the regional data in the LCI database, more questionnaire responses are necessary from local ready mix concrete plants.

Table 4.14 Comparison between ready mix concrete questionnaire responses and literature values

	Unit*	Plant 1	Plant 2	Zapata et al., 2005	PCA, 2007
Energy use	Mbtu	51,315	252,900	11,820	31,020
Notes	--	Energy used for: Plant generator	Energy used for: Plant generator	Energy used for: Mixing operation	Energy used for: Plant operation

* Energy values are based on the production of 1 yd^3 of concrete

4.2.6 Recycled materials in asphalt mixtures

Recycled materials in asphalt mixtures usually refer to RAP and RAS. Four questionnaire responses were collected for RAP production including RAP crushing/screening, stockpiling, and storage. It was assumed that the milling process did not contribute much on the energy consumption so it was not included in the RAP questionnaire. General information on RAP questionnaire responses is shown in Table 4.15.

Table 4.15 Summary of questionnaire responses for RAP

	Plant 1	Plant 2	Plant 3	Plant 4
Reporting period	07/2012 – 09/2012	07/2012 – 09/2012	03/2012 – 09/2012	05/2012 – 08/2012
Production	25,000 tons	12,000 tons	21,934 tons	181,336 tons
Notes	No data given (resources and emissions are inseparable from HMA plant)	No data given (fuel usage is inseparable from HMA plant)	All RAP products blended with concrete	Emissions included with HMA plant data

Only one questionnaire response was received on RAS. The production stage for RAS includes metal/waste removal operation, grinding, trammel and storage. The general information on the RAS questionnaire is shown in Table 4.16.

Table 4.16 Summary of questionnaire response for RAS

	Plant 1
Reporting period	01/2012 – 09/2012
Production	47,204 tons
Notes	RAS fraction: • RM-98 • Moisture content (%): 10 ~ 14

Energy consumption for the production of RAP is presented in Table 4.17. Since Plants 1 and 2 provided no data on energy consumption only data for Plants 3 and 4 are shown in Table 4.17. The energy use in Plant 3 was exactly five times higher than that in Plant 4 because the fuel use by Fractionated Recycled Asphalt Pavement (FRAP) machine was much higher in Plant 3. The average energy value of these two was taken and included in the LCI database for RAP. For RAS, both the amount of fuel use and energy per ton of RAS production are presented in Table 4.18. Diesel was used throughout the production of RAS and the amount of fuel use for transportation and processing was about the same. The total energy consumption for RAS was the sum of these two production stages.

Table 4.17 Energy consumption during the production of RAP

	Unit*	Plant 1	Plant 2	Average
Diesel (from loaders)	Gal	0.132	0.057	0.0945
Diesel (from FRAP machine)	Gal	0.371	0.043	0.207
Total energy	Btu	70,000	14,000	42,000

* The fuel volume and energy value are based on the production of 1 ton of RAP

Table 4.18 Energy consumption during the production of RAS

	Fuel* (gal)	Energy* (Btu)
Diesel (in-plant transportation, loaders)	0.686	94,000
Diesel (generator, grinding, trammel)	0.675	92,000
Total	1.361	187,000

* The fuel volume and energy value are based on the production of 1 ton of RAS

By comparing the energy consumption to produce one ton of RAP and one ton of RAS, it was found that the production of RAS required about 3 times more energy than RAP per unit mass. However, if our assumption that the effect of RAP milling is insignificant turns out to be incorrect in the future study, the gap between energy values can be reduced.

4.2.7 Supplementary cementitious materials

Supplementary cementitious materials (SCMs) refers to fly ash, slag cement, silica fume, or other pozzolanic materials used in conjunction with Portland or blended cement in order to contribute to the properties of hardened concrete (PCA, n.d.). The use of SCMs can reduce the amount of cement in concrete and/or achieve a higher compressive strength. Although silica fume can dramatically increase the strength of hardened concrete the cost of silica fume is too high for pavement use. Fly ash and slag cement are relatively inexpensive because they are by-products of other industrial processes. The production of these materials needs not be considered because of double counting. For example, in the production of precast concrete, 100% of the environmental burden of fly ash is allocated to electricity generation (NPCA, 2010). Therefore, including the upstream process of fly ash would constitute double counting if the electricity is used in the system. Similarly, the upstream process of slag cement is already considered in steel production. However, if the data on the production of SCMs becomes available, future study that includes the downstream process of production will be included in the LCI database. As mentioned in the scope of the study, the transportation of SCMs was considered.

4.3 Summary of the Collected Data

Table 4.19 compares the energy consumption and GHG emissions of various material production activities. In terms of energy use, the production of cement required the most energy per ton whereas the production of RAP required the least energy. Only two questionnaire responses had data for GHGs. The production of cement was once again responsible for the greater GHG emission as compared to the production of HMA.

Table 4.19 Summary of questionnaire responses on energy use and CO_2EQ emission

Material Process	Energy (Btu/ton)	CO_2EQ (ton/ton)	Source
HMA	588,000	0.02685	Average of Plants 1 and 2
Aggregate(CM)	103,000	N/A	Plant 1
Aggregate(FM)	103,000	N/A	Plant 1
RAS	187,000	N/A	Plant 1
RAP	42,000	N/A	Average of Plants 3 and 4
Cement	3,290,000	0.6827	Plant 1
Ready-mix	74,000	N/A	Average of Plants 1 and 2

Not all questionnaire responses were ultimately incorporated into the LCI database. For some material productions, literature values were used instead due to the reliability and discrepancy between collected data and literature values. Table 4.20 shows the sources for the final LCI database.

Table 4.20 Summary of sources for the final LCI database

Material Process	Source
HMA	Average of Plants 1 and 2
Aggregate(CM)	PCA (2007)
Aggregate(FM)	PCA (2007)
RAS	Plant 1
RAP	Average of Plants 3 and 4
Cement	Plant 1
Ready-mix	PCA (2007)

4.4 Impact Assessment

Life-cycle impact assessment (LCIA) is the third phase of an LCA. LCIA includes the categorization of the environmental impacts from various emissions and a quantitative assessment between LCI results and category indicators using characterization factors (ISO, 2006). Characterization factors are conversion factors that convert and combine the LCI results into representative indicators of impacts on human and ecological health (U.S. EPA, 2006). Since the impact category of interest in the study was global warming potential (GWP) only GWP characterization factors were used. These characterization factors are based on a 100-year time horizon, the most commonly used time frame for GWP. The characterized unit for GWP is CO_2 equivalent (CO_2EQ). The characterization factors provided by EPA TRACI v2 (Bare, 2012) were used to calculate CO_2EQ in this study. Table 4.21 summarizes the elements of LCIA mentioned above. Although the only impact category of interest was GWP, emissions other than GHGs were also collected and kept in the LCI database for future use.

Table 4.21 Summary of LCIA elements

<table>
<tr><th>Element</th><th colspan="2">Values</th></tr>
<tr><td>Impact category</td><td colspan="2">Global warming potential (GWP)</td></tr>
<tr><td>LCI results</td><td colspan="2">Amount of greenhouse gases (CO_2, CH_4, N_2O)</td></tr>
<tr><td>Category indicator</td><td colspan="2">CO_2 equivalent (CO_2EQ)</td></tr>
<tr><td rowspan="2">Characterization factors
(100-year time frame)</td><td>Inventory item</td><td>CO_2EQ</td></tr>
<tr><td>Carbon dioxide, CO_2
Methane, CH_4
Nitrous oxide, N_2O</td><td>1
25
298</td></tr>
</table>

CHAPTER 5. MOBILE VEHICLE EMISSION ESTIMATION

In 2011, transportation was the second largest source of greenhouse gas (GHG) emissions in the U.S. after electricity generation (U.S. EPA, 2012). The emissions are primarily created from burning fossil fuels such as gasoline, diesel and liquefied petroleum gas (LPG) by vehicles. Greenhouse gases and various other air pollutants are emitted from all on-road and non-road moving vehicles. It is very important to precisely estimate vehicle emissions in pavement LCA for the following reasons:

- The vehicle emission is related to all phases of pavement LCA through hauling of raw materials to the plants and from the plants to the job site and vehicles using the roads during their service life
- The amount of vehicle emissions and fuel use during the service life of a road can be significantly greater than the energy used and emissions from an entire pavement construction process (Santero, 2009). According to Santero (2009), the emissions from just the use phase can be many times greater than that of all other LCA phases combined
- Fuel usage and emission can vary significantly due to actual traffic, road surface and stiffness, road geometry, vehicle and tire characteristics, and environmental conditions

Therefore, it is critical to estimate fuel use and emission from all moving vehicles including light and heavy vehicles (such as hauling trucks) and construction vehicles. This chapter introduces methodology followed to estimate emissions for hauling trucks using EPA’s Mobile Vehicle Emissions Simulator (MOVES). The same methodology may be applied to all other moving vehicles as part of future works.

5.1 Introduction to MOVES Software

EPA’s Mobile Combustion Source document (U.S. EPA, 2008) contains generic GHG emission factors for mobile vehicles and equipment. This study currently uses these generic emission factors for moving vehicles. However, many important parameters are not included in these emission factors. The following is a list of parameters that affect vehicle emission factors:

- Seasonal variation (changes in temperature and relative humidity)
- Vehicle driving patterns (average speed and acceleration)
- Types of vehicles (passenger cars and trucks)
- Road grades
- Link length and number of vehicles

EPA's MOVES is an open source software program that is written in Java, using MySQL as its database system. A graphical user interface (GUI) allows users to access inputs and outputs to the database system. Using the interface, users can also upload formats such as Excel spreadsheets to specify input parameters to be used in MOVES. A default database has been built into the MOVES model that contains national data and factors to estimate regional data for 3,222 counties in the United States (U.S. EPA, 2012).

MOVES software was developed to replace an old vehicle emission simulator, called MOBILE6.2 also developed by the EPA. Compared to MOBILE6.2, MOVES is capable of estimating more emissions and its framework is much more flexible with many input and output options (U.S. EPA, 2012). The main purpose of using MOVES is related to the software's ability to estimate the missions from moving vehicles with changing speed, temperature, humidity, traffic, and road parameters. The software is capable of estimating vehicle emissions and energy use for numerous cases in which users may be interested. By changing input files and using MOVES' default databases, users can analyze vehicle emissions at national, county, and project levels. The simplified structure of MOVES is illustrated in Figure 5.1.

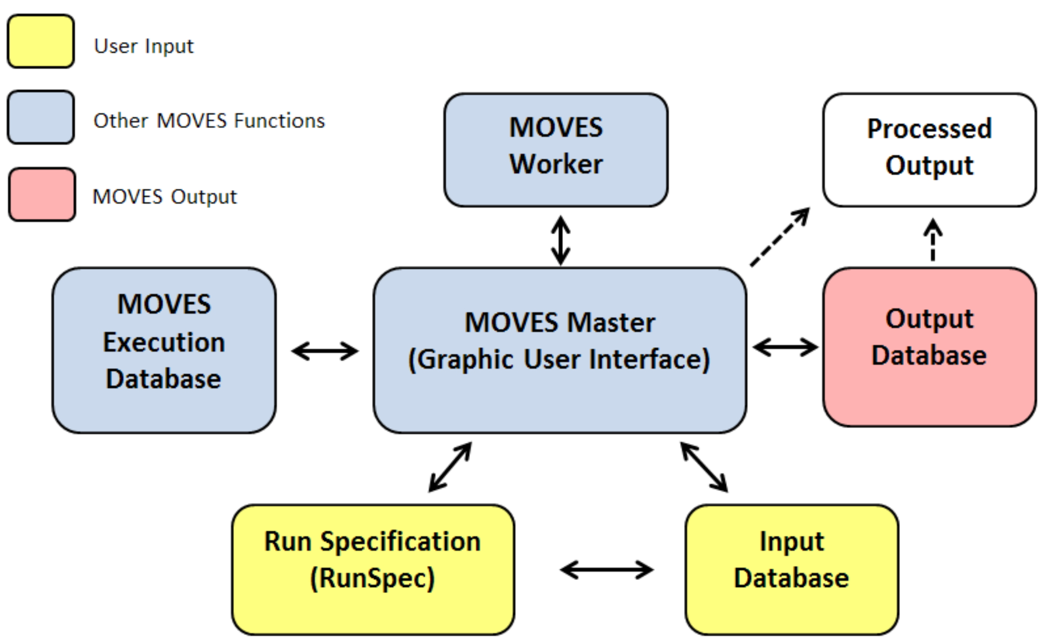


Figure 5.1 The simplified structure of MOVES (after Dresser et al., 2012)

Input databases can be either default or user-created, but most of the time users provide local specific data because the use of the default database is restricted to certain situations. The execution database does not directly interact with users and the database is only used for a particular run. The results of the simulations are saved in the output database. MOVES Master is the core process unit that takes inputs from users and default databases and releases the results to the output database as seen in Figure 5.1.

5.1.1 Observations on preliminary simulations using MOVES

After understanding the capability and structure of MOVES, preliminary simulations were run to examine the relationship between vehicle emissions and some important parameters such as vehicle speed, link length, road grades, temperature and humidity. The preliminary simulations were performed at the project level and the settings used are shown in Table 5.1. The purpose of the simulation was not to observe the interactions among parameters but it is rather to evaluate the change in vehicle emissions due to one parameter change at a time.

Table 5.1 Summary of background information for preliminary runs

Parameters	Units	Values
Year	--	2010
Month	--	July
Day	--	Weekdays
Hour	--	7:00 – 8:00 am
Temperature	°F	70.1
Relative humidity	%	78.5
State	--	Illinois
County	--	Cook
Road type	--	Urban restricted
Link length	Mile	1
Link volume	Vehicles	1,000,000
Link average speed	Mph	70
Link average grade	%	0
Vehicle (source) type	--	Combination long-haul trucks

The time (year, month, day, and hour) and geographic (state and county) information are used to retrieve temperature and relative humidity values from the MOVES default database. The specific values of temperature and relative humidity for the time and location given in Table 5.1 are 70.1 °F and 78.5%, respectively. With this meteorological information, other traffic parameters are assumed so that a precise emission data set can be generated from the simulations. This study focuses specifically on urban highways in the northern Illinois area (Cook County) so the appropriate road type is urban restricted.

5.1.1.1 Temperature and relative humidity

Since the MOVES database contains meteorology data from 3,222 counties in the country, annual temperature and relative humidity information of nearly any location in the U.S. can be extracted from the database. The meteorology data are not organized in terms of date but in terms of month and hour. In other words, a set of temperature and relative humidity values will be assigned to a unique combination of month and hour. Using the default setting shown in Table 5.1, the values of temperature and relative humidity were changed while all other variables were kept unchanged. Figure 5.2 illustrates how CO_2 emissions change with respect to the change in temperature and relative humidity.

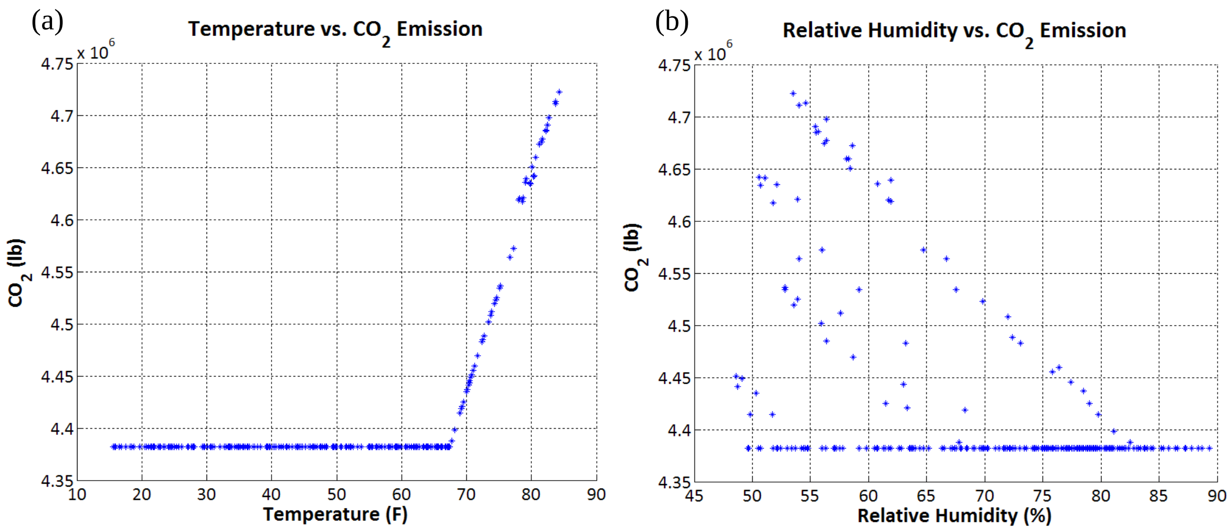


Figure 5.2 Change in CO_2 emission with respect to (a) temperature and (b) relative humidity

Figure 5.2 (a) shows the change in CO_2 emission with respect to temperature. The amount of emissions remained constant at a low temperature but begins to increase linearly when it reached 67°F. A report by the EPA explained that the operation of air conditioning due to hot temperature could be the reason for a sudden change in the emission trend (U.S. EPA, 2011). Figure 5.2 (b) shows the relationship between the CO_2 emission and relative humidity. The emissions remained constant at 4.36 x 10^6 lb at any relative humidity. In other words, the change of relative humidity did not affect the CO_2 emissions in this particular case. There were some points above the line of constant emission but they were negligible because these temporarily raised emission values were due to temperature variation in this particular simulation.

5.1.1.2 Link length and link volume

A link is a section of a roadway to be analyzed. At the project level, users assign a set of parameters to define a particular link. Link length and link volume are two of these parameters and the relationship between emissions and these two parameters were determined by simulations. From simulations, both link length and volume were expected to have a linear relationship between CO_2 emission and energy. The result of the simulations is shown in Figure 5.3.

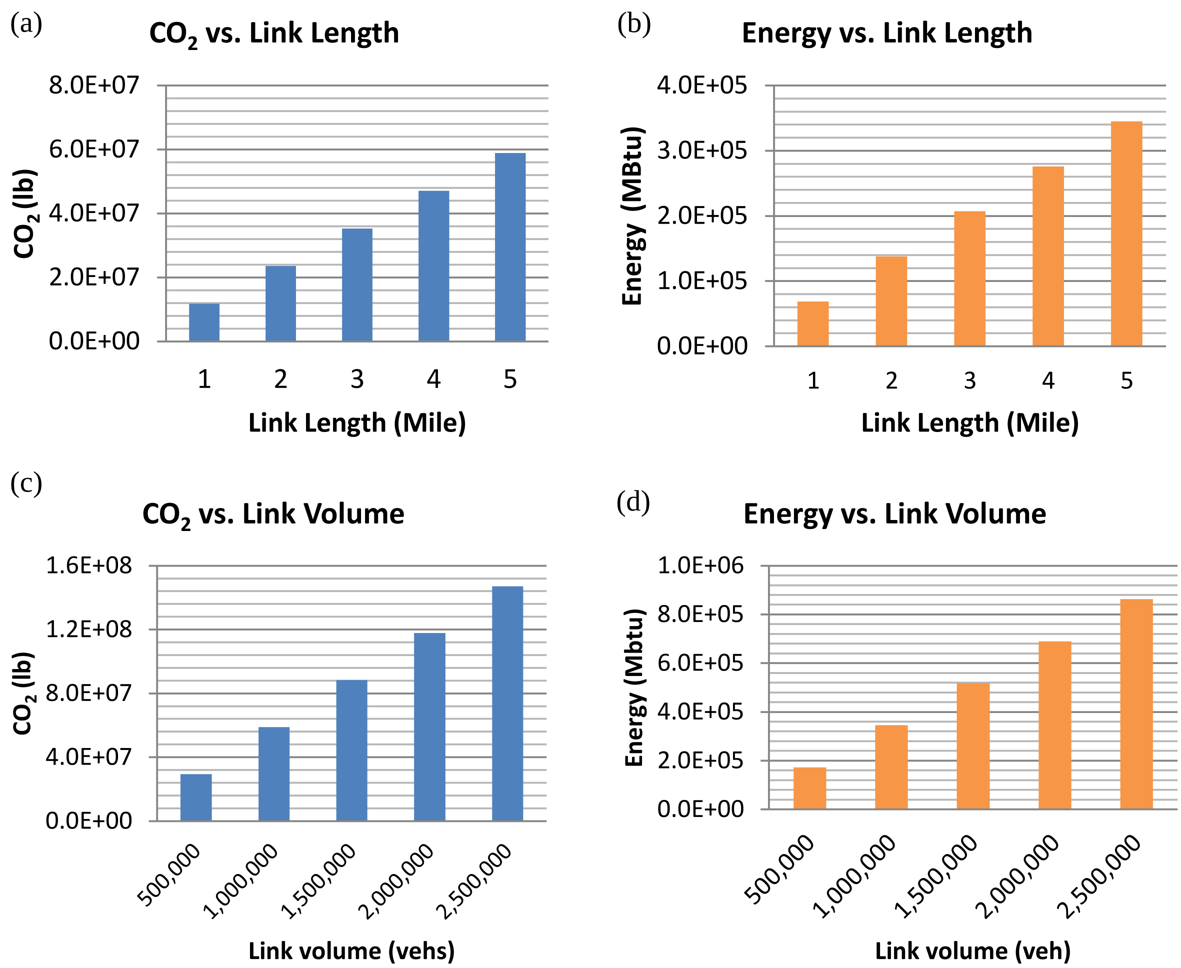


Figure 5.3 Change in (a) CO_2 emission and (b) energy with respect to link length, and change in (c) CO_2 emission and (d) energy with respect to link volume

5.1.1.3 Link average speed

In order to observe how link average speed affects vehicle emissions, simulations were performed at various speeds ranging from 40 to 85 mph, at increments of 5 mph. As the study is focused on the urban highways, the range of speed was assumed to be greater than 40 mph and less than 85 mph. The CO_2, PM_{10}, NO_x emissions and energy were plotted with respect to the speed change in Figure 5.4. Figures for other emissions such as GHGs (CH_4, N_2O), CO, and SO_2 are shown in Appendix C.

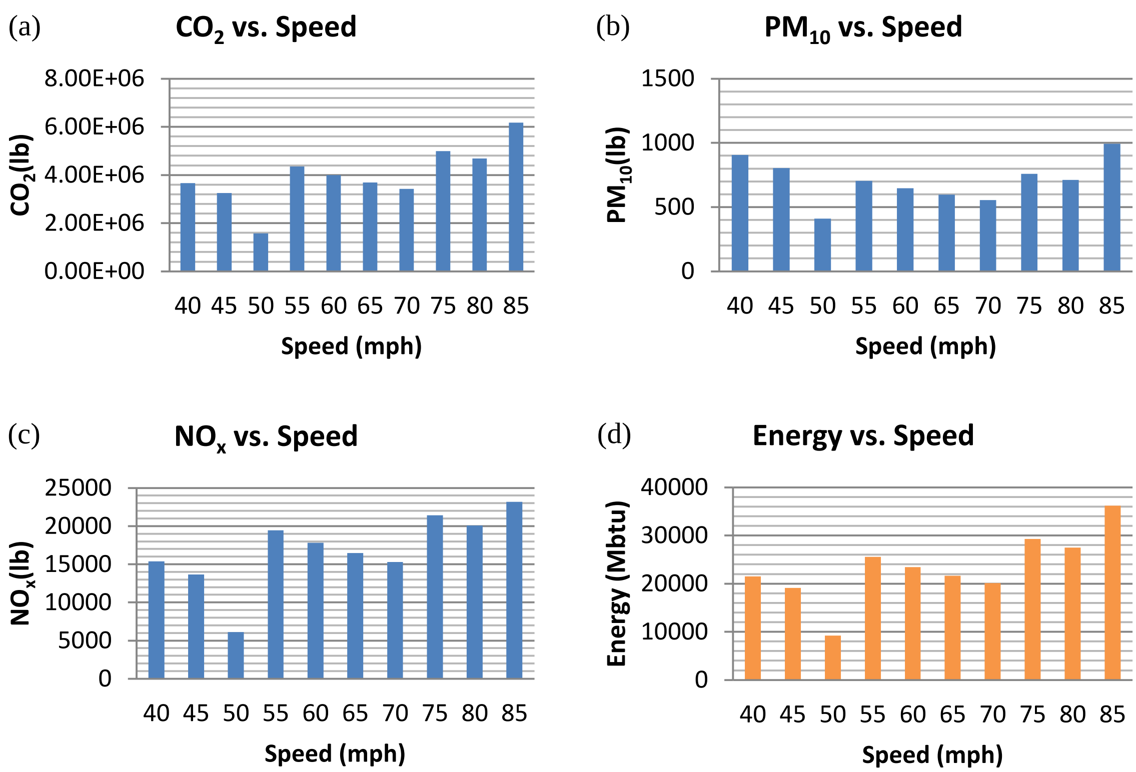


Figure 5.4 Change in (a) CO_2, (b) PM_{10}, (c) NO_x emissions and (d) energy with respect to speed

As seen in Figure 5.4, the trend of all three changes in emissions and energy turned out to be similar. The highest emissions and energy consumption were observed at 85 mph while the lowest emissions and energy were observed at 50 mph. It was notable that a low speed did not necessarily mean a low emission or energy consumption. The model seemed to suggest that there was an optimum speed to minimize certain emissions and energy consumption. From this simulation, the optimum speed seemed to be around 50 mph.

5.1.1.4 Road grade

MOVES also accounts for the average road grade (in %) of a particular link. Simulations were performed to determine the effect of road grade change on vehicle emissions. The setup of the simulation was based on the information provided in Table 5.1. The result of the simulation showed that there is a linear relationship between emissions and road grade. However, the linear relationship tended to cease when the road grade reached 4%. Figure 5.5 illustrates the result of road grade simulations for CO_2 emission and energy using link driving schedules.

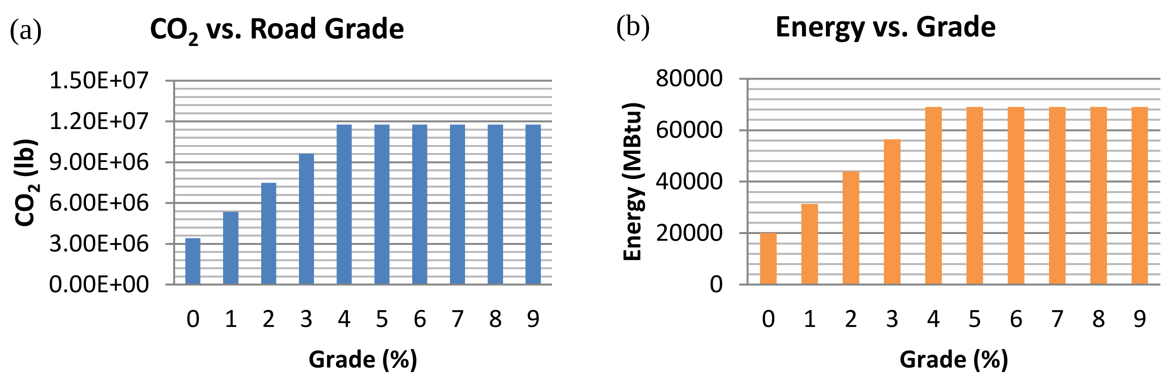


Figure 5.5 Change in (a) CO_2 emission and (b) energy with respect to road grade using link driving schedules

A similar trend in CO_2 emission and energy was found when simulations with the same condition were performed using operating mode distribution. When using link driving schedules, there was an abrupt change in CO_2 emission and energy at the road grade of 4%. However, when using operating mode distribution, the CO_2 emission and energy tended to converge at a road grade of around 8% as seen in Figure 5.6. The values of CO_2 emission and energy were different for two particular cases as link driving schedule used an exact speed whereas operating mode distribution used an average speed. From these two cases, the impact of road grade seems to converge at a certain point and it is probably because the road grade is one of the parameters affecting vehicle specific power (VSP), which influences vehicle emissions.

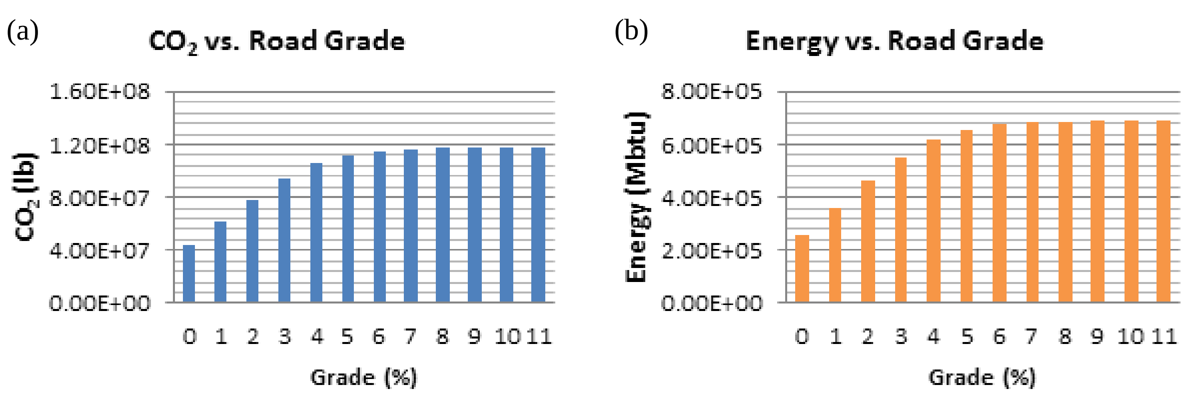


Figure 5.6 Change in (a) CO_2 emission and (b) energy with respect to road grade using operating mode

5.1.1.5 Vehicle Source type

The amount of emissions varies greatly with the vehicle's weight and type. Depending on the weight of the vehicles, the fuel type and fuel consumption rate changes; thus, the corresponding emissions and energy usage also changes. This section attempted to analyze emissions and energy consumption among six types of vehicles: passenger cars, refuse trucks, single unit short-haul trucks, single unit long-haul trucks, combination short-haul trucks, and combination long-haul trucks. For simplicity, a unique source type number was assigned to each vehicle type as shown in Table 5.2. From this point on, source type and source type number would be used interchangeably.

Table 5.2 Source type numbers and corresponding source types

Source type	Source type number
Passenger cars	21
Refuse trucks	51
Single unit short-haul trucks	52
Single unit long-haul trucks	53
Combination short-haul trucks	61
Combination long-haul trucks	62

Using the default information from Table 5.1, a simulation was performed for each type of vehicle. The results of this simulation are shown in Figure 5.7.

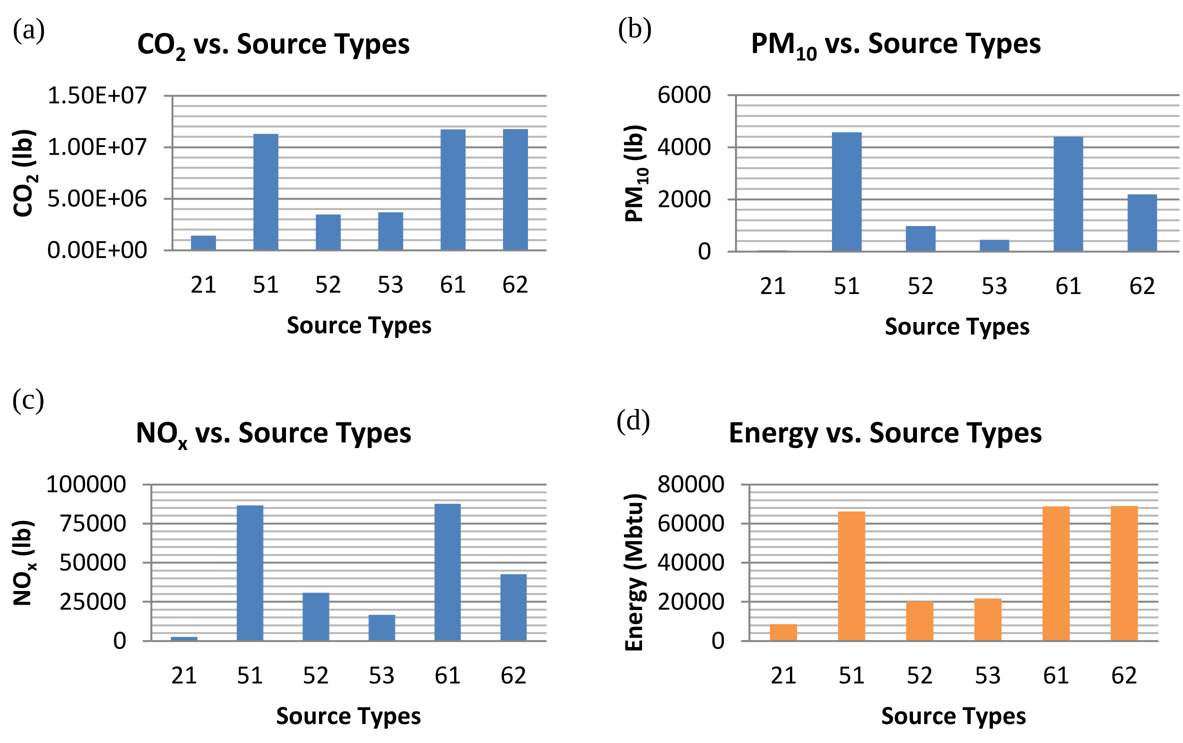


Figure 5.7 Change in (a) CO_2, (b) PM_{10}, (c) NO_x emissions and (d) energy with respect to various source types

Each source type has a different fixed mass (U.S. EPA, 2010), contributing to significant differences in the emissions and energy among source types as seen in Figure 5.7. The highest CO_2 emissions and energy consumption were observed in source type 62; the highest PM_{10} emission was observed in source type 51; and the highest NO_x emission was observed in source type 61. Source type 62 is the heaviest vehicle of all source types (U.S. EPA, 2010) but it did not necessarily have the highest values in all types of emissions. On the other hand, the lowest emissions and energy consumption were both observed in source type 21 possibly because passenger cars have a mass significantly smaller than the other source types.

5.2 Updated Emission Factors for Mobile Vehicles

As mentioned in the previous section, current emission factors for mobile vehicles have limitations because many important parameters affecting vehicle emission rates are not included. This section attempted to compute emission factors for each source type at the fixed speed of 55 mph. This speed was selected because it is assumed to represent the average speed of material hauling vehicles. Table 5.3 describes the background information for emission factor simulations. The information is similar to what is shown in Table 5.1 but the link length was changed to 10 miles from 1 mile in order to obtain more accurate data. Link speed and grade were fixed throughout the link instead of taking an average speed and grade, meaning that the speed and grade were set to remain exactly at 55 mph and 0%, respectively. In addition, emission factors were generated for six source types based on the information given in Table 5.3.

Table 5.3 Summary of background setting for emission factor simulations

Parameters	Units	Values
Year	--	2010
Month	--	July
Day	--	Weekdays
Hour	--	24 hours
Temperature	°F	70.1
Relative humidity	%	78.5
State	--	Illinois
County	--	Cook
Road type	--	Urban restricted
Link length	Mile	10
Link volume	Vehicles	1,000,000
Link fixed speed	Mph	55
Link fixed grade	%	0
Vehicle (source) type	--	21, 51, 52, 53, 61,62

As mentioned in the previous chapter, construction activities usually take place during relatively warm seasons; therefore the month of July was assumed to represent this time period. In a project scale analysis, the time interval of each simulation is one hour. However, simulating just a specific time does not factor in hourly temperature and relative humidity variations. In order to observe an hourly variation of emissions, simulations were performed over all 24 hrs. Figure 5.8 demonstrates how CO_2 emission and energy changed with respect to hourly variation. The figures are for source type 62 only but the other source types also showed similar variations. The CO_2 emission and energy seemed to be lowest around 7:00 am but highest around 4:00 pm. The variations for other emissions such as NO_x and SO_2 are shown in Appendix C.

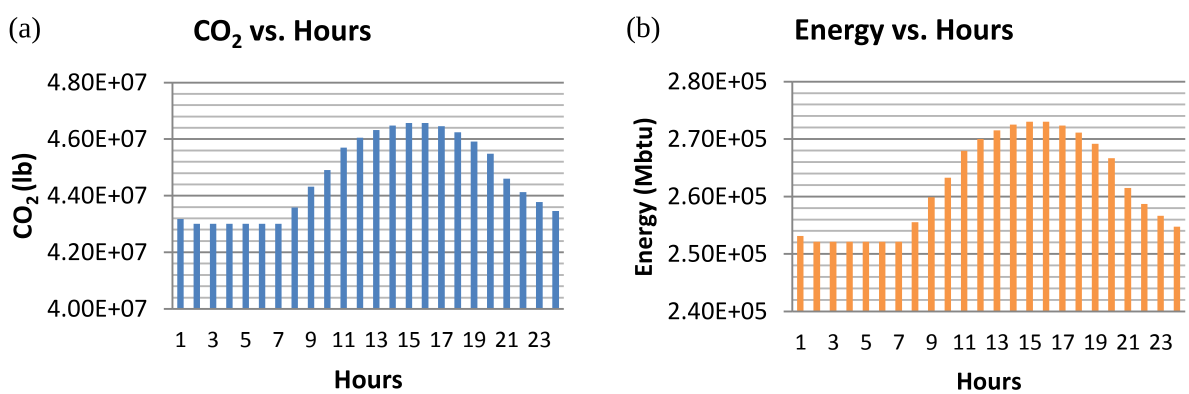


Figure 5.8 Hourly variations of (a) CO_2 emission and (b) energy

In order to reflect hourly variations in emissions and energy, the average values of 24 hrs were taken to be representative values of emissions and energy for July. Based on these average values of emissions and energy, emission factors for six source types were calculated. The desired unit for emission factors was *pounds per vehicle-mile* (lb/vehicle-mile). MOVES has an option to show total distance traveled for each simulation. Each source type had a different total distance traveled as shown in Table 5.4, so the values of emissions and energy had to be normalized with respect to total distance traveled to obtain emission factors.

Table 5.4 Total distance traveled for six source types

Source types	Total distance traveled (miles)
21	9,975,270
51	9,598,080
52	6,481,300
53	6,912,810
61	9,981,460
62	10,002,000

Based on the information provided in Table 5.3, the product of link length and link volume is 10,000,000 vehicle-miles (10 miles x 1,000,000 vehicles). The total distance traveled for source type 21, 51, 61, and 62 are close to 10,000,000 vehicle-miles, but those for source type 52 and 53 were significantly smaller than other source types as shown in Table 5.4. However, the emission factors were normalized with respect to total distance traveled so this discrepancy did not affect the emission factors. In order to prove that the data can be normalized, linear relationship between travel length and energy and emissions should be established. A series of simulations were performed by changing link length and link volume to see how they contributed to the variations in emissions and energy. Five different link volumes (100, 1,000, 10,000, 100,000, and 1,000,000) and corresponding CO_2 emissions and energy were plotted in log scale graphs. In this simulation, the link length was kept constant at 10 miles. As seen in Figure 5.9, CO_2 emission and energy had a linear relationship at a wide range of link volumes.

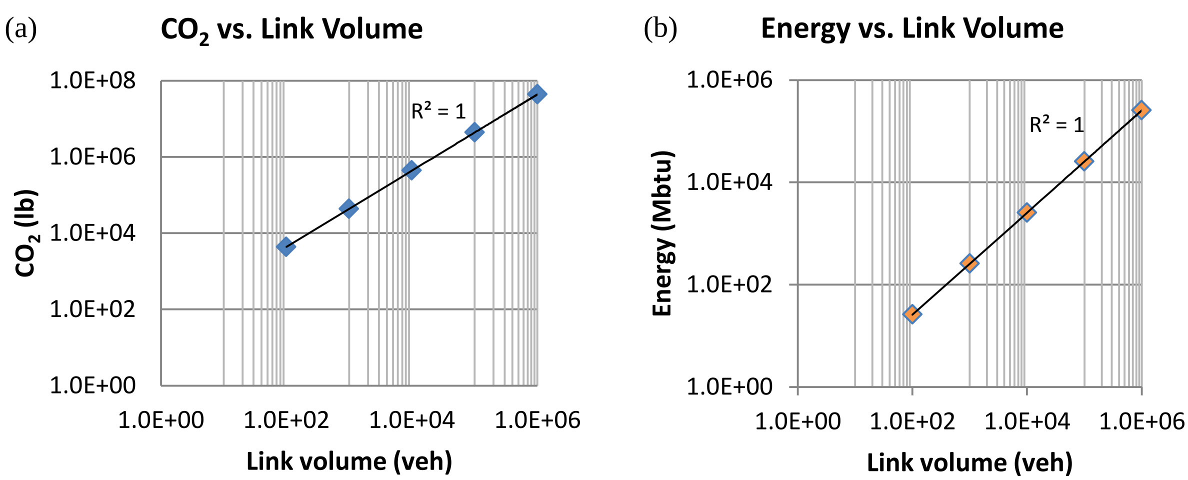


Figure 5.9 Change in (a) CO_2 and (b) energy with respect to link volume

For link length simulations, both link length and link volume varied so that the product of link length and link volume was kept constant at 10,000,000 vehicle-miles. For example, if the link length was 10 miles, the link volume was 1,000,000 vehicles; if the link length was 20 miles, the link volume was 500,000 vehicles. It was found that the values of CO_2 emission and energy were constant up to a link length of 55 miles, but after this point the values of CO_2 and energy began to decrease. Therefore, any link length values of less than 55 miles were considered acceptable to use. In the simulation, the link length was 10 miles so it was accepted as an appropriate assumption. The result of link length simulations are graphically presented in Figure 5.9.

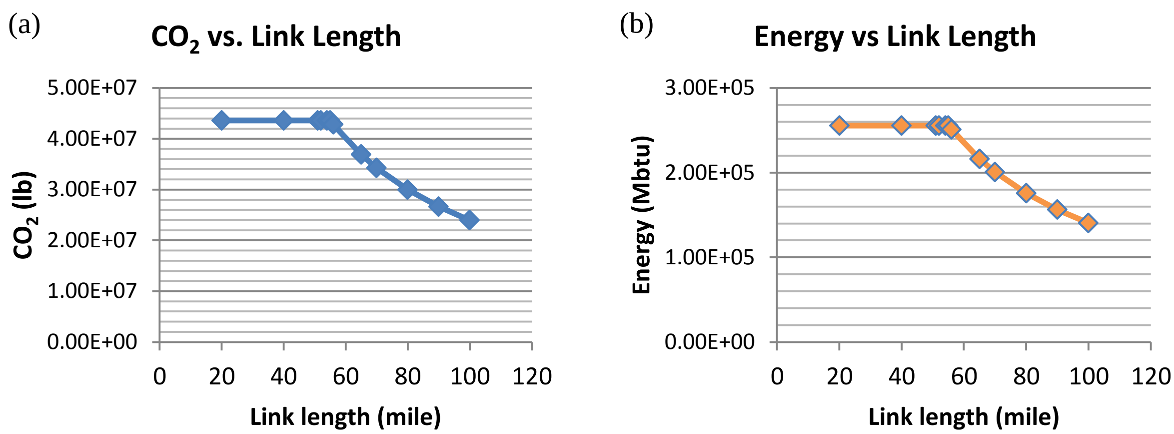


Figure 5.10 Change in (a) CO_2 emission and (b) energy with respect to link length

The final emission factors for six source types are tabulated in Table 5.5. The calculated emission factors varied with source type. For CO_2 emission, source type 62 had the highest emission factor while source type 21 had the lowest emission factor. Similarly, source type 62 had the highest factor whereas source type 21 had the lowest factor in terms of energy. The results were considered acceptable because source type 62 is the heaviest vehicle type and tends to consume more fuel per unit distance. For other air emissions, no clear trend was determined; but in general source type 21 had the lowest factors for most emissions except for carbon monoxide (CO) because the typical fuel type used for source type 21 is gasoline and it is known to emit more CO than diesel (Bloom, 2010).

Table 5.5 Various emission factors per 1 vehicle-mile for six source types at a fixed speed of 55 mph

Source Type	CO_2 (lb)	CH_4 (lb)	N_2O (lb)	CO (lb)	NO_x (lb)	SO_2 (lb)	PM_{10} (lb)	$PM_{2.5}$ (lb)	Energy (Mbtu)
21	0.654	7.60E-06	5.41E-06	3.50E-03	8.77E-04	1.28E-05	1.09E-05	1.00E-05	3.91E-03
51	1.475	1.94E-05	3.33E-06	6.11E-03	8.92E-03	1.18E-05	7.24E-04	7.02E-04	8.65E-03
52	1.474	2.05E-05	3.24E-06	5.12E-03	9.21E-03	1.17E-05	8.67E-04	8.41E-04	8.64E-03
53	1.477	4.04E-05	3.33E-06	3.37E-03	6.19E-03	1.12E-05	4.47E-04	4.34E-04	8.66E-03
61	4.458	2.11E-05	3.31E-06	7.34E-03	3.89E-02	3.51E-05	1.28E-03	1.24E-03	2.61E-02
62	4.465	3.83E-05	3.30E-06	4.23E-03	1.93E-02	3.40E-05	7.05E-04	6.84E-04	2.62E-02

These new vehicle emission factors obtained from MOVES simulations will be used to replace the existing vehicle emission factors in the existing LCI database. Therefore, the emissions and energy consumption associated with material transportation are expected to be measured in a more reliable and accurate way.

5.3 Validation of Updated Emission Factors

In order to validate the new emission factors, equivalent emission factors were retrieved from commercial LCA software, *SimaPro7.3.3,* and an existing LCA tool, *PE-2*, for comparison. SimaPro LCA software has been widely used around the world for its comprehensive data and it uses the ecoinvent database. For simplicity, the ecoinvent database will be referred to as *SimaPro database* in this study. PE-2 has also been considered to be a reliable LCA tool for roadway projects. Thus, referencing these two databases can help us determine the adequacy of new emission factors. In addition, existing EPA's mobile emission factors (U.S. EPA, 2008) were used to assess the change in new emission factors. Due to lack of data availability in other platforms, only emission factors for heavy trucks were compared in this section; Table 5.6 summarizes these emission factors from the aforementioned various sources.

Table 5.6 Summary of emission factors for heavy trucks from various sources

Emissions (per veh-mile)	Unit	MOVES	SimaPro 1*	SimaPro 2**	PE-2	U.S. EPA, 2008
CO_2	lb	4.46	4.04	3.33	2.56	2.60
CH_4	lb	3.83E-05	3.85E-05	3.85E-05	--	1.14E-05
N_2O	lb	3.30E-06	3.13E-05	3.36E-05	--	1.06E-05
CO	lb	4.23E-03	7.00E-03	6.25E-03	--	--
NO_x	lb	1.93E-02	3.83E-02	3.40E-02	--	--
SO_2	lb	0.34E-04	1.28E-04	1.05E-04	--	--
PM_{10}	lb	7.05E-04	2.01E-04	2.01E-04	--	--
$PM_{2.5}$	lb	6.84E-04	9.40E-04	9.74E-04	--	--

* Based on the operation data of a lorry > 30.9 tons, fully loaded
** Based on the operation data of a lorry 22.0 – 30.9 tons, fully loaded

There was only one type of hauling truck in the PE-2 database compared with the 24 types represented in the SimaPro database. According to FHWA's report (Alam et al., 2007), the average weight of a combination truck in Illinois is about 35.9 tons. Thus, a fully loaded lorry truck heavier than 30.9 tons was selected as a representative truck type from SimaPro database. For reference, information on a fully loaded lorry truck between 22.0 and 30.9 tons was also added in Table 5.6. For MOVES, the source type 62, combination long-haul truck, was selected as the truck type for a comparison.

In terms of CO_2 emission, the new emission factors from MOVES simulations were about 9.4%, 25%, 43%, and 42% greater than SimaPro 1, SimaPro 2, PE-2, and the old emission factors, respectively. The difference between MOVES and SimaPro 1 was only 9.4%, which may suggest that the new CO_2 emission factor is comparable to that in a commercial database. By comparing SimaPro 1 and SimaPro 2, the CO_2 emission decreased by nearly 18% as the truck weight decreased. Other emission factors from simulations were of the same order of magnitude to those from the SimaPro database except for nitrous oxide (N_2O). This discrepancy is attributed to a combination of several parameters such as geographical location, speed and weight of trucks.

The average payload and the average empty weight of a combination truck with 6 axles for Illinois are about 19.8 tons and 16.1 tons, respectively (Alam et al., 2007). Summing the weights, the average gross weight of a heavy duty truck is 35.9 tons. In MOVES, the average gross weight and the fixed mass factor of a combination long-haul truck are 34.6 tons and 18.8 tons, respectively (U.S. EPA, 2010). MOVES software assumes that the fixed mass factor of 18.8 tons represents the average running weight of all heavy-duty vehicles (U.S. EPA, 2010). Based on this information, the unit of new emission factors for source type 62 was converted from *lb per vehicle-mile* to *lb per ton-mile*. This converted unit may be helpful in calculating emissions from hauling in terms of the mass of materials transported. The result of the conversion is shown in Table 5.7.

Table 5.7 The updated emission factors for heavy trucks per ton-mile

Emissions (per ton-mile)	Unit	MOVES
CO_2	lb	2.38E-01
CH_4	lb	2.04E-06
N_2O	lb	1.76E-07
CO	lb	2.25E-04
NO_x	lb	1.03E-03
SO_2	lb	1.81E-06
PM_{10}	lb	3.75E-05
$PM_{2.5}$	lb	3.64E-05

CHAPTER 6. CASE STUDIES USING LCA TOOL

A pavement LCA tool with a regionalized LCI database was developed at the University of Illinois. In the previous chapters, the development of the LCI database and vehicle emission factors are addressed. Follows are several case studies using the developed inventory database and vehicle emission factors.

6.1 Background on Case Studies

The background information such as project details and the pavement structure of the case studies are introduced. In order to simulate a realistic pavement LCA result, information from an actual roadway construction project is used. The general project information is summarized in Table 6.1.

Table 6.1 Summary of a roadway construction project

Items	Project information
Route	Interstate-90 (I-90)
Roadway length	7.6 miles
Number of lanes	3 lanes
Design life	Perpetual
Type of pavements	Full depth hot-mix asphalt (HMA)
Description	Roadway and bridge reconstruction

This specific case study considered three pavement layers: wearing surface, binder course and base course. Assuming that pavement shoulders are not considered, a total of seven mix designs were used for the three layers. The thicknesses and mix designs for each layer are summarized in Table 6.2. The project files included the amount of each mix used in the actual construction. A percentage value was obtained using this information to represent one-lane mile with each one of these mixes.

Table 6.2 Information on surface, binder and base course of pavements

Pavement layer	Mix designs	Thickness (in)	% used
Surface course	• 90BIT0941 – Surface	2.0	19.5
Binder course	• 90BIT0845 – Binder	3.5	11.4
	• 90BIT0811 – Binder	3.5	14.3
	• 90BIT0939 – Binder	3.0	15.2
	• 90BIT0908 – Binder	2.0	10.3
Base course	• 90BIT0843 – Base	3.0	13.9
	• 90BIT0810 – Base	3.5	15.4
		Total	100.0 %

The mix design information was also retrieved from the project files. Details on materials used for each mix design and hauling distances are described in Table 6.3. The information included stockpile percentages, aggregate quarries, plant location, binder type and supplier.

Table 6.3 Materials used in various mix designs

Mix design	Material	Name	% by Mass	Distance (mile)
90BIT0941 (Surface)	CM-XX Crushed	031CM14, 031CM13	44.5 + 31.0 = 75.5	0
	FA-XX Crushed	039FM20	6.0	0
	Mineral filler	004MF01	5.5	173
	RAP*	CAT 1 Fine	13.0	0
	GTR** binder (15%)	PG 76-22	4.0	130
90BIT0845 (Binder)	CM-XX Crushed	042CM11, 032CM16	36.0 + 32.0 = 68.0	0
	FA-XX Crushed	038FM20	11.0	0
	Mineral filler	004MF01	1.0	0
	RAP	> 4 FRAP***, < 4 FRAP	8.5 + 11.5 = 20.0	0
	Straight binder	PG 58-22	5.2	98.7
90BIT0811 (Binder)	CM-XX Crushed	022CM11, 032CM16	28.0 + 41.0 = 69.0	0
	FA-XX Crushed	038FM20	10.0	0
	Mineral filler	004MF01	1.0	139
	RAP	CAT 1 Fine, CAT 2 Coarse	10.0 + 10.0 = 20.0	0
	Straight binder	PG 58-22	5.4	41.2
90BIT0939 (Binder)	CM-XX Crushed	031CM14, 031CM13	47.0 + 31.5 = 78.5	34.7
	Mineral filler	004MF01	6.5	143
	RAP	CAT 1 Fine	15.0	0
	GTR binder (15%)	PG 76-22	6.0	98.7
90BIT0908 (Binder)	CM-XX Crushed	031CM14, 031CM13	40.0 + 38.5 = 78.5	0
	Mineral filler	004MF01	6.5	173
	RAP	CAT 1 Fine	15.0	0
	GTR binder (15%)	PG 76-22	6.1	130
90BIT0843 (Base)	CM-XX Crushed	042CM11, 032CM16	25.5 + 18.0 = 43.5	0
	FA-XX Crushed	037FA01	6.5	4.1
	RAP	> 4 FRAP, < 4 FRAP	24.0 + 26.0 = 50.0	0
	Straight binder	PG 58-28	5.0	98.7
90BIT0810 (Base)	CM-XX Crushed	022CM11, 032CM16	22.0 + 24.0 = 46.0	0
	FA-XX Crushed	037FM01	8.0	13.5
	Mineral filler	004MF01	1.0	139
	RAP	CAT 2 Fine, CAT 2 Coarse	21.0 + 24.0 = 45.0	0
	Straight binder	PG 58-28	4.9	41.2

* RAP = Reclaimed Asphalt Pavement
** GTR = Ground Tire Rubber
*** FRAP = Fractionated Reclaimed Asphalt Pavement

For the mix design, 90BIT0941, *90* stands for I-90, *BIT* stands for asphalt, and *0941* is a unique mix design number. For materials, *CM* stands for coarse aggregate, *FA* stands for fine aggregate, and mineral filler is a material such as fly ash used to fill the void of flexible or rigid pavements. For name, in 042CM11, the first two digits indicates the quality of aggregate, the third digit indicates the type of stone, and the last two digits represents the material's intended gradation (IDOT, 2013). A similar naming method is used for fine aggregate (FA). FRAP is classified based on its size. If FRAP material is retained on the #4 sieve, it is *< 4 FRAP*, but if it passes the #4 sieve, it is *> 4 FRAP*. In PG 76-22, *PG* stands for the *performance grade* of the asphalt binder, *76* is the maximum pavement design temperature in $^{\circ}$C, and *22* is the minimum temperature in $^{\circ}$C (Foo, 2012). The % by mass indicates the ratio of the mass of each material to the total mass of the mix design. Distance indicates the hauling distance from the stockpile or storage tank of each material to mix plants.

6.2 Analysis of a Case Study Using the LCA Tool

Given the background information in the previous section, the LCA tool is now ready to calculate emissions and energy for the reconstruction of a roadway section on I-90. Once the mix designs for each pavement layer are inputted, the LCA tool automatically computes the corresponding emissions and energy consumption per functional unit — one lane-mile. Figure 6.1 shows the global warming potential (GWP) and energy consumption per lane-mile for each layer. Figures for other emissions such as particulate matter (PM) and volatile organic compound (VOC) are shown in Appendix D.

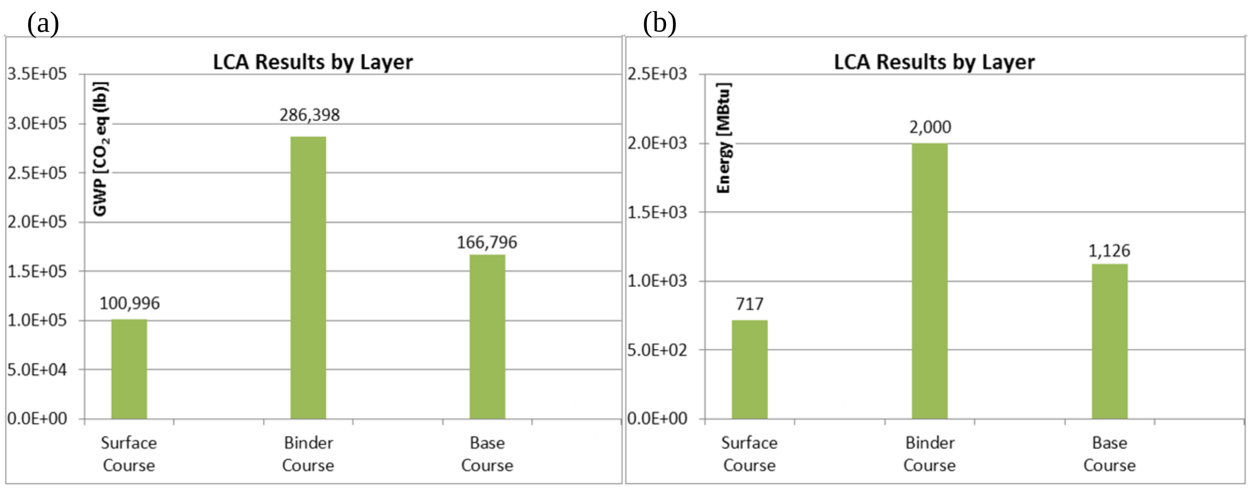


Figure 6.1 (a) GWP and (b) energy consumption per lane-mile for a roadway reconstruction project

In this particular case study, the base course had the highest GWP and energy consumption. This stands to reason, as the layer was responsible for more than half of the entire material by weight. PM and VOC emissions also showed a pattern similar to GWP and energy consumption.

The results of the case study were limited to surface, binder, and base courses; pavement shoulders, subbase, and subgrade were not considered in this study. In addition, the results of the case study were expected to reflect the regional emissions and energy to some extent rather than displaying national average values. However, as more regional data are collected the LCI database will be updated and the results generated by the LCA tool will be more regionalized.

6.3 Sensitivity to Transportation Distances and Emission Factor Choices

In order to observe the effect of the updated emission factors on the GHG emissions of the pavement LCA, a sensitivity analysis was performed with various updated emission factors presented in Table 5.6. The case study shown in this section displays only the results for GWP; it is the only impact category considered at this point. The case study is based on the same highway construction project mentioned in the previous section.

Figure 6.2 shows the results of a sensitivity analysis of GWP with respect to transportation distances. The GWP using an original hauling distance as well as hauling distances of five and ten times greater than the original distance is presented.

The values of GWP for the three cases are summarized in Table 6.4. As Table 6.4 suggests, the impact of an increase in hauling distance can be quite significant. If the hauling distance increases by factors of 5 and 10, the GWP for the entire material phase increases by 11.2% and 20.3%, respectively. The GWP changes after the vehicle emission factors were updated and are presented in Table 6.5 and Figure 6.3 for five vehicle emission factors.

Table 6.4 Summary of the sensitivity analysis with respect to hauling distances

	GWP (lb CO_2 EQ per 1 lane-mile)			
Distance	**Surface course**	**Binder course**	**Base course**	**Total**
Original hauling distance	101,682	167,979	291,342	561,003
5 times greater than original distance	108,071	174,493	341,751	624,315
10 times greater than original distance	116,057	182,636	404,761	703,454

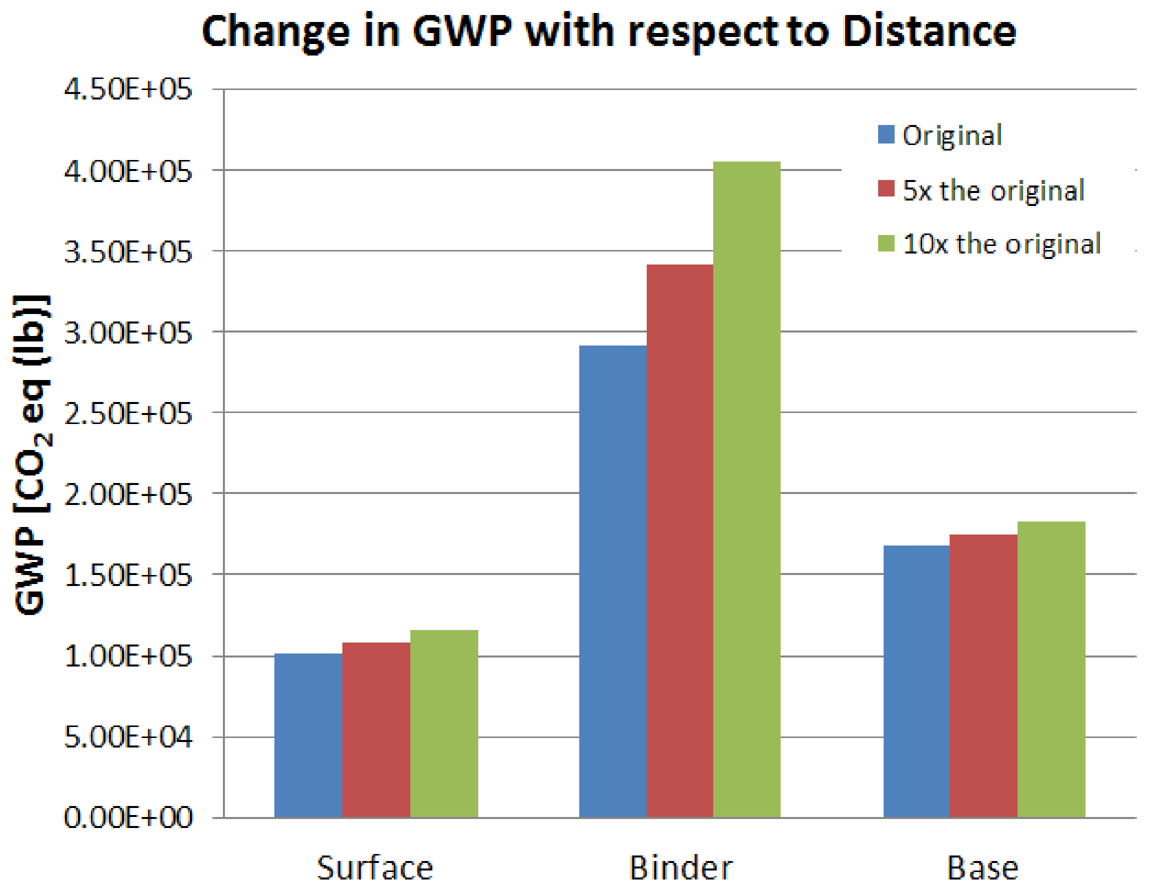


Figure 6.2 A sensitivity analysis of GWP by layers using an original distance, a five times the original distance, and a ten times the original distance

Table 6.5 Summary of GWP values for five different vehicle emission factors

Source of emission factor	**Global warming potential (CO_2EQ per one lane-mile)**			
	Surface	**Binder**	**Base**	**Total**
MOVES simulation	101,682	291,342	167,979	561,003
SimaPro1*	101,530	290,247	167,717	559,494
SimaPro2**	101,268	288,357	167,265	556,890
PE-2	100,980	286,280	166,768	554,028
EPA, 2008	100,996	286,398	166,796	554,190

* Based on the operation data of a lorry > 30.9 tons, fully loaded

** Based on the operation data of a lorry 22.0 – 30.9 tons, fully loaded

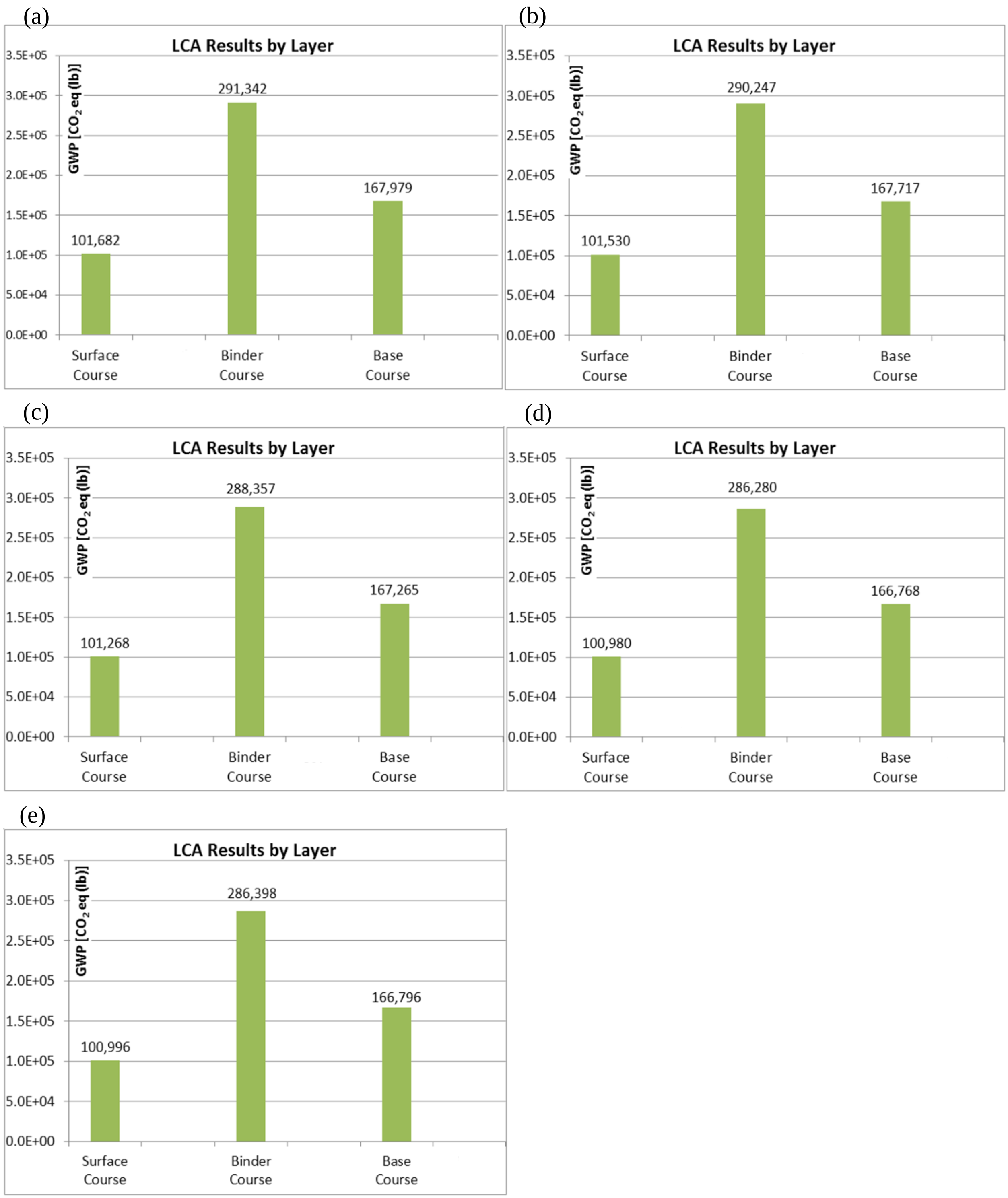


Figure 6.3 The GWP with respect to five different vehicle emission factors: (a) MOVES, (b) SimaPro1, (c) SimaPro2, (d) PE-2, (e) old emission factors

MOVES simulation resulted in the highest GWP values, while PE-2 resulted in the smallest. As the EPA emission factors were updated to those from MOVES simulation, there was a 1.2% increase in GWP per one lane-mile as seen in Table 6.5. The difference can be considered insignificant for short distance hauling. However, as seen in Figure 6.2, as the hauling distance increases, the impact of transportation becomes more significant. Thus, it may be possible that a slight change in vehicle emission factors can significantly affect the GWP of the material phase if the hauling distances become relatively long.

CHAPTER 7. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

The preliminary works for the development of an LCA tool with regional inventory database was presented in this study. The ultimate goal was to perform a pavement LCA study at a regional level, using locally collected materials data in Illinois. The outcome of the materials phase of the data collection was presented and used to create a regional pavement LCI database containing information on various emissions and energy consumption. In addition, in order to accurately account for the fuel use and emissions from mobile vehicles, the existing emission factors were updated through simulations using EPA's newest vehicle emission estimator, MOVES. The preliminary results from the developed LCA tool were presented for a case study. Sensitivity analysis was also conducted to assess the importance of hauling distances and vehicle emission assumptions.

7.2 Findings and Conclusions

A summary of the findings and conclusion on the pavement LCA is compiled in the following for literature, data collection and inventory development, and traffic simulations:

Literature findings:

- There were four studies reviewed in the literature comparing flexible and rigid pavements. In terms of energy consumption, one study (Stripple, 2001) reported that flexible pavements had a lower impact on the environment, while two other different studies (Athena Institute, 2006; Zhang et al., 2008) reported that rigid pavements had a lower environmental impact.
- In terms of CO_2 emissions, two studies (Stripple, 2001; Santero, 2009) reported that flexible pavements had less impact on the environment, one study (Zhang et al., 2008) reported that flexible and rigid pavements had a similar level of CO_2 emission, and one study (Athena Institute, 2006) reported rigid pavements had a lower environmental impact.

Data collection and inventory database development for material phase of pavement LCA:

- An inventory database containing the life-cycle emissions and energy consumption of major pavement materials was developed. Regionally collected questionnaire responses were recorded in the database after data quality check. Some reported values from the literature were also used to supplement the missing data.

- In terms of energy consumption to produce one ton of aggregate, the questionnaire responses were nearly four times higher than the reported values by PCA (2007).
- Since questionnaire responses lacked upstream process information for asphalt binder production, literature data were used for the inventory database. Economic and mass allocation methods were used in the literature (Eurobitume, 2011).
- Depending on the type of HMA plant, the energy consumption per ton of HMA production changed significantly. The energy consumption in Plant 1 was comparable to the literature value; Plant 3 had about seven times greater energy consumption than found in the literature (Stripple, 2001; Zapata et al., 2005); it was a retail type of plant.
- For cement, both the CO_2 emission and energy consumption from questionnaire responses were comparable to those in the study by PCA (2006).
- In the ready-mix concrete plant questionnaires, Plant 1 reported almost double the energy consumption of the PCA study; while Plant 2 reported values nearly eight times higher (PCA, 2007).
- For one ton of recycled materials, the energy consumption for RAS production was about four times greater than RAP production.
- In terms of energy consumption per ton for all productions considered, based on the questionnaire responses, cement production was the largest source, followed by HMA, RAS, aggregate, ready-mix, and RAP, respectively.

MOVES simulation results suggest the following findings:

- The CO_2 emissions were sensitive to temperature changes. The emissions tended to increase in a hot season due to the operation of air conditioning.
- The CO_2 emissions and energy use tended to increase linearly as link volume increased. As link length increased, the CO_2 emissions and energy increased up to a certain point but stabilized shortly thereafter.
- The CO_2, PM_{10}, NO_x, SO_2 emissions and energy consumption changed with vehicle speed. Between 40 and 85 mph, the CO_2, PM_{10}, NO_x, SO_2 emissions and energy were the lowest at around 55 mph and the highest at 85 mph. For CH_4, N_2O, and CO emissions, the highest emissions were observed at 40 mph and the lowest emissions at 85 mph.
- The CO_2 emissions and energy increased linearly up to 4% road grade but stabilized after this.

- The emissions and energy were related to vehicle types. In general, heavier vehicles were responsible for more CO_2 emission and higher energy use. However, other emissions such as PM_{10} and NO_x did not behave in a similar trend.
- The CO_2, NO_x, SO_2 emissions and energy changed with respect to hourly variations.
- Mobile vehicle emission factors generated from MOVES simulations were used in lieu of existing emission factors in order to predict emissions more accurately and measure more various air emissions.
- A sensitivity analysis for GWP suggests that an increase in hauling distances can significantly increase the GWP of the entire material phase.

Based on thus study, the following conclusions can be drawn:

1. A regional life-cycle inventory was developed for flexible and rigid pavements.
2. Literature review revealed that pavement LCA depends on the system boundaries and assumptions.
3. Data quality check is very important in building a robust life-cycle inventory database.
4. The emission factors from MOVES simulations are comparable to those reported in the literature and commercial databases. Considering temporal and spatial characteristics would improve the accuracy of vehicle emission prediction.
5. The GWP in the material phase depends significantly on the hauling distances.

7.3 Recommendations for Future Research

Inventory database development is one of the most critical and time consuming components of LCA. This study presented the first phase of data collection from regional sources as well as from other open source databases. Data quality and representativeness is a key for a robust and reliable LCA. Therefore, it is highly recommended to collect data from trusted sources (if possible commercial databases such as SimaPro and GaBi) and regional sources such as manufacturers, suppliers, and producers. It was observed in the first round of regional data collection that the reliability of data collected through surveys can be questionable. Since there are no environmental regulations for such data for most of the pavement products, data shall be obtained from the literature or collected questionnaires. These questionnaires should be designed carefully to retrieve accurate information from sources. It is also highly recommended to hold on-site interviews to achieve better data collection.

The importance of transportation on emissions related to the hauling of raw materials to the plant and from the plant to the job site was emphasized in the study. However, accurate emission factors for all moving vehicles (off-road and on-road) are critical for a pavement LCA. Therefore, it is important to continue to use MOVES simulations to develop emission factors that will reflect the impact for vehicle emissions during the service life of a pavement as well as during traffic delays that occur with construction activities. In addition, other models or databases are needed to develop emission factors for off-road vehicles used in construction activities. Finally, it is recommended to develop a complete and friendly LCA tool that can be used by agencies, engineers, and contractors.

REFERENCES

Al-Qadi, I. (2012). *Pavement Introduction* [PDF document]. Retrieved on August 27, 2012, from Lecture Notes.

Alam, M. & Rajamanickam, G. (2007). *Development of Truck Payload Equivalent Factor*. Washington, DC: Federal Highway Administration (FHWA).

Asphalt Paving Environmental Council. (2007). *Best Management Practices to Minimize Emissions during HMA Construction* (1st ed.). Lanham, MD: Asphalt Paving Environmental Council (APEC).

Athena Institute. (2001). *A Life Cycle Inventory for Road and Roofing Asphalt*. Ottawa, Canada: Franklin Associates.

Athena Institute. (2006). *A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential*. Ottawa, ON, Canada: Athena Institute.

Bare, J. (2012). Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) (Version 2.1) [Software]. Cincinnati, OH.

Bloom, A. (2010). *In The Encyclopedia of Earth online*. Retrieved on May, 2013 from http://www.eoearth.org/article/Comparing_Diesel_to_Gasoline?topic=54483

Dresser, C., & Laurita, M. (2012, August). *Introduction to MOVES for Non-Modelers* [PDF document]. Retrieved from http://www.dvrpc.org/NTAQS/pdf/MOVES_training.pdf.

Emissions & Generation Resource Integrated Database (eGRID) 2012 (ver1). [Software]. (2012). Washington, DC: U.S. Environmental Protection Agency.

Eurobitume. (2011). *Life Cycle Inventory: Bitumen*. Brussels, Belgium: European Bitumen Association.

Federal Highway Administration (FHWA) (2012). Public Road Length by Functional System, 1980 – 2007. Retrieved on May 19, 2013, from http://www.fhwa.dot.gov/policyinformation/statistics/hm20_summary.cfm

Foo, K. (2012). Performance Graded (PG) Binder. California Department of Transportation. Retrieved on July 10, 2013, from http://www.dot.ca.gov/hq/maint/Pavement/Offices/Pavement_Engineering/PG_Binder.html

Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) (rev2) [Computer software]. (2012). Chicago, IL: Argonne National Laboratory.

Illinois Department of Transportation (IDOT) (2013). *Specific Gravity (Gsb) List*. Retrieved on May 19, 2013 from http://www.dot.state.il.us/materials/aggregatespecificgravity.pdf

International Organization for Standardization (ISO) (1997). *Environmental Management – Life Cycle Assessment - Principles and Framewor*k (ANSI/ISO 14040).

International Organization for Standardization (ISO) (2006). *Environmental management – Life Cycle Assessment – Requirements and Guidelines* (ISO 14044:2006).

Meadows, D. H., Meadows, D. L., Randers, J. & Behrens, W. (1972). *The Limits to Growth: a Report for the Club of Rome's Project on the Predicament of Mankind*. New York, NY: Universe Book.

Michigan Tech. (2011). PE-2 [Software]. Accessed on June 10, 2013 http://www.construction.mtu.edu/cass_reports/webpage/index.html

Morrison Hershfield., the Athena Institute., Venta, Glaser & Associates. (2010). Life Cycle Assessment of Precast Concrete Belowground Infrastructure Products. Seattle, WA: National Precast Concrete Association.

Overview of Greenhouse Gases. (2011). Retrieved on June13, 2013, from http://www.epa.gov/climatechange/ghgemissions/gases.html

Park, K., Hwang, Y., Seo, S., and Seo, H. (2003). *Quantitative Assessment of Environmental Impacts on Life Cycle of Highways*. J. Constr. Eng. Manage., 129(1), 25-31.

Portland Cement Association. (2006). *Life Cycle Inventory of Portland Cement Manufacture* (serial No. 2095b). Skokie, IL: Marceau, M. L., Nisbet, M. A., & VanGeem, M. G.

Portland Cement Association. (2007). Life Cycle Inventory of Portland Cement Concrete (serial No. 3011). Skokie, IL: Marceau, M. L., Nisbet, M. A., & VanGeem, M. G.

Portland Cement Association (n.d.). Concrete Technology. Cement.org. Retrieved May 30, 2013, from http://www.cement.org/tech/cct_concrete_prod.asp#scm.

Pre. (2012). SimaPro LCA Software (Version 7.3.3) [Software]. Available from http://www.pre-sustainability.com/download-software

Santero, N. J., Masanet, E., & Horvath, A. (2011). Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation and Recycling, 55*(9-10), 801-809. Retrieved from www.scopus.com

Santero, N. (2009). *Pavements and the environment: a life-cycle assessment approach*. Retrieved from ProQuest Digital Dissertations.

Stripple, H. (2001). Life Cycle Assessment of Road: A Pilot Study for Inventory Analysis (report No. B1210E) (2nd ed.). Goethenburg, Sweden.

University of California Pavement Research Center (UCPRC) (2010). Pavement Life Cycle Assessment Workshop (report No. UCPRC-TM-2010-03). Davis, CA.

U.S. Department of Energy. (n.d.). Guidelines for Voluntary Greenhouse Gas Reporting (report No. 6450-01-P). Washington, DC: Office of Policy and International Affairs.

U.S. Department of Transportation. (2006). *Freight in America: A New National Picture*. Washington, DC: Research and Innovative Technology Administration. Retrieved from http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/freight_in_america/pdf/entire.pdf

U.S. Department of Transportation (2010). *2007 Economic Survey: Transportation: 2007 Commodity Flow Survey* (publication No. EC07TCF-US). Washington, DC: Bureau of Transportation Statistics and U.S. Census Bureau. Retrieved from http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/commodity_flow_survey/final_tables_december_2009/pdf/entire.pdf

U.S. Environmental Protection Agency (U.S. EPA). (2004). Compilation of Air Pollutant Emissions Factors, AP-42: Chapter 11.1. Washington, DC: Office of Air Quality Planning and Standards.

U.S. Environmental Protection Agency. (2006). *Life Cycle Assessment: Principles and Practice* (publication No. EPA/600/R-06/060). Cincinnati, OH: Scientific Application International Corporation (SAIC).

U.S. Environmental Protection Agency. (2008). Direct Emissions from Mobile Combustion Sources (report No. EPA430-K-0-004). Washington, DC: Office of Air and Radiation.

U.S. Environmental Protection Agency (U.S. EPA). (2010). *MOVES2010 Highway Vehicle: Population and Activity Data*. Ann Arbor, MI: Assessment and Standards Division, EPA.

U.S. Environmental Protection Agency (U.S. EPA). (2011). *MOVES Sensitivity Analysis: The Impacts of Temperature and Humidity on Emissions*. Ann Arbor, MI: Choi, D. et al.

U.S. Environmental Protection Agency (U.S. EPA). (2012). Motor Vehicle Emission Simulator (MOVES): User Guide for MOVES2010b (report No. EPA-420-B-12-001b). Washington, DC: Office of Transportation and Air Quality.

Wang, T., Lee, I. S., Harvey, J., Kendall, A., Lee, E. B., & Kim, C. (2012). *UCPRC Life Cycle Assessment Methodology and Initial Case Studies on Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance* (UCPRC-RR-2012-02). Davis, CA: University of California Pavement Research Center.

Zapata, P. & Gambatese, J. (2005). *Energy Consumption of Asphalt and Reinforced Concrete Pavement Materials and Constructio*n. J. Infrastr. Syst. 11, Special issue: sustainability of transportation and other infrastructure systems, 9-20. Technical papers.

Zhang, H., Keoleian, G.A., & Lepech, M. D. (2008). An integrated life cycle assessment and life cycle analysis model for pavement overlay systems. Paper presented at the Life-Cycle Civil Engineering – Proceedings of the 1st international Symposium on Life-cycle Civil Engineering, IALCCE ’08, 907-912. Retrieved from www.scopus.com

APPENDIX A

Results of Indirect Energy and Emissions Calculations Using GREET and eGRID

Table A.1 Indirect energy and emissions for fossil fuels based on GREET

Item (Unit per fuel unit)	Coal to power plants	Conventional gasoline	Liquefied petroleum gas	Natural gas stationary fuels	Petroleum coke	Residual oil	Conventional Diesel	Crude Oil Extraction (8% oil sand)
Fuel Unit	per ton	per gal	per gal	per 1000 ft3	per ton	per gal	per gal	per gal
Energy (Btu)	4.57E+05	2.33E+04	1.72E+04	9.60E-02	8.24E+06	1.66E+04	2.57E+04	8.09E+03
VOC (lb)	3.81E-01	6.85E-03	1.59E-03	1.27E-08	3.51E-01	1.57E-03	2.29E-03	1.03E-03
CO (lb)	1.29E-01	3.00E-03	2.27E-03	1.75E-08	7.71E-01	2.78E-03	3.33E-03	1.65E-03
NO_x (lb)	6.37E-01	1.18E-02	9.17E-03	5.04E-08	3.07E+00	1.27E-02	1.31E-02	7.95E-03
PM_{10} (lb)	8.67E+00	1.75E-03	1.30E-03	1.91E-09	7.72E-01	1.42E-03	1.92E-03	7.68E-04
$PM_{2.5}$ (lb)	2.16E+00	9.80E-04	7.36E-04	1.21E-09	3.12E-01	8.66E-04	1.08E-03	4.74E-04
SO_x (lb)	3.59E-01	6.61E-03	4.89E-03	2.55E-08	2.15E+00	6.23E-03	7.24E-03	3.49E-03
CH_4 (lb)	7.41E+00	3.75E-02	2.75E-02	1.18E-06	1.12E+01	3.81E-02	4.15E-02	3.09E-02
N_2O (lb)	1.54E-03	5.60E-05	4.18E-05	2.06E-10	2.17E-02	4.18E-05	6.20E-05	2.05E-05
CO_2 (lb)	7.94E+01	4.15E+00	3.07E+00	1.16E-05	1.30E+03	3.01E+00	4.60E+00	1.51E+00
CO_2 EQ (lb)	2.66E+02	5.13E+00	3.78E+00	4.12E-05	1.59E+03	3.98E+00	5.66E+00	2.30E+00

Table A.2 Indirect energy and emissions for electricity based on eGRID's Illinois mix data

	Unit per kWh	Electricity (IL)
Energy	Btu	0.00E+00
NO_x	lb	7.58E-04
SO_x	lb	2.48E-03
CH_4	lb	1.22E-05
N_2O	lb	1.74E-05
CO_2	lb	1.07E+00
GHGs	CO_2 EQ	1.07E+00

APPENDIX B

A Sample Questionnaire Template

CEMENT PRODUCTION

Confidential Life Cycle Inventory Survey

PART 1: GENERAL PRODUCTION INFORMATION

Questionnaire completed by: ____

Plant Location (city, state): ____

Plant Type: ____

Raw Meal Preparation

Type of cement	Type of raw mill (i.e. ball, roller):	# of raw mills	Average productivity (ton/day)	Average electricity usage (kWh/ton)

Clinker Production

Type of cement	Type of kiln (i.e. dry, preheater/precalciner):	# of raw mills	Average productivity (ton/day)	Average electricity usage (Mbtu/ton)

Finish Grinding

Type of cement	Type of mill (i.e. ball, roller):	# of mills	Average productivity (ton/day)	Average electricity usage (kWh/ton)

Reporting period (preferably consecutive 6 or 12 months): ______________________________

Total Production (tons): ____________________ Average Daily Production (tons): ____________________

Average Actual Operation

Hours/Year: __________ Hours/Day: __________ Days/Week: __________ Weeks/Year:__________

Water Usage (gals) per ton of cement produced

Total Used: ________________ Recycled into other processes: ______________ Disposed:____________

Waste (tons) per ton of cement produced: ____________

As determined for Type ______ cement, per TON of cement produced

PART 2a: FUEL AND ENERGY USE USED IN QUARRYING and RAW MEAL PREPARATION

Resource/Energy Use *(excluding in-plant transportation, see below)*	**Total per ton of cement**	**Unit**	**Alt Unit**	**Remarks** *(i.e. specify what purpose or others)*
Electricity (public grid) - **CRUSHING**		kWh		
Electricity (public grid) - **GRINDING**		kWh		
Electricity (public grid) – **OTHERS**		kWh		
Natural gas		yd^3		
Gasoline		gal		
Middle distillates				
No. 1, 2[4] and 4 diesel fuel		gal		
No. 1, 2 and 4 fuel oil		gal		
Residual oils or heavy distillates				
No. 5 and 6 fuel oil		gal		
Explosives		lb		
		–		

In-Plant Transportation Equipment (backhoe loader, wheel loader, dump truck, conveyor belt etc.) and model	**Purpose**	**Fuel Type (Diesel–D, Gasoline-G) Specify if others**	**Efficiency (gal/hr or kWh/hr)**	**Productivity (ton/hr)**

[4] Please indicate sulfur content (if no. 2 diesel used)

Figure B.1 A sample questionnaire template

APPENDIX C

Results of MOVES Simulations

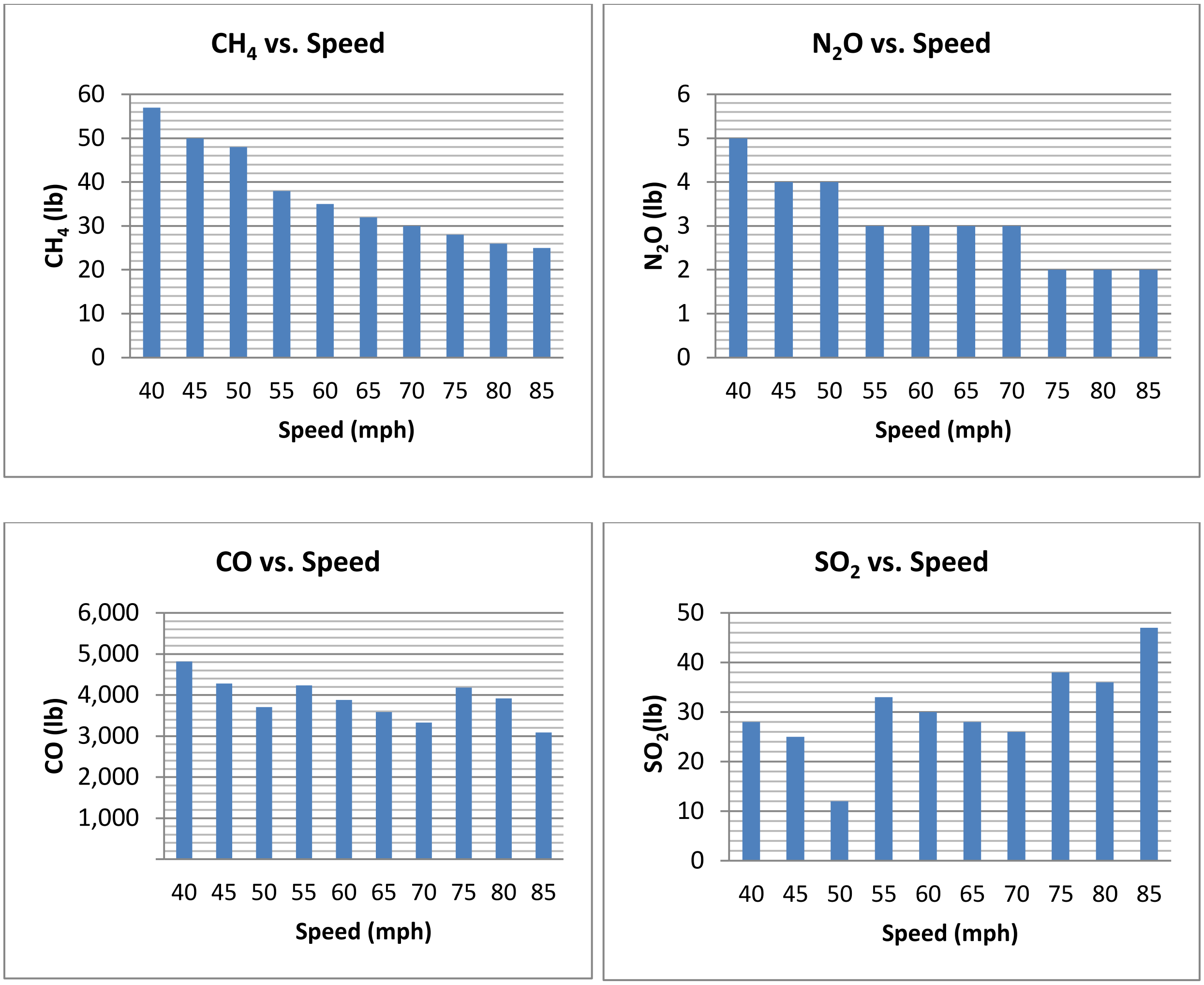


Figure C.1 Change in CH_4, N_2O, CO, and SO_2 emissions with respect to speed

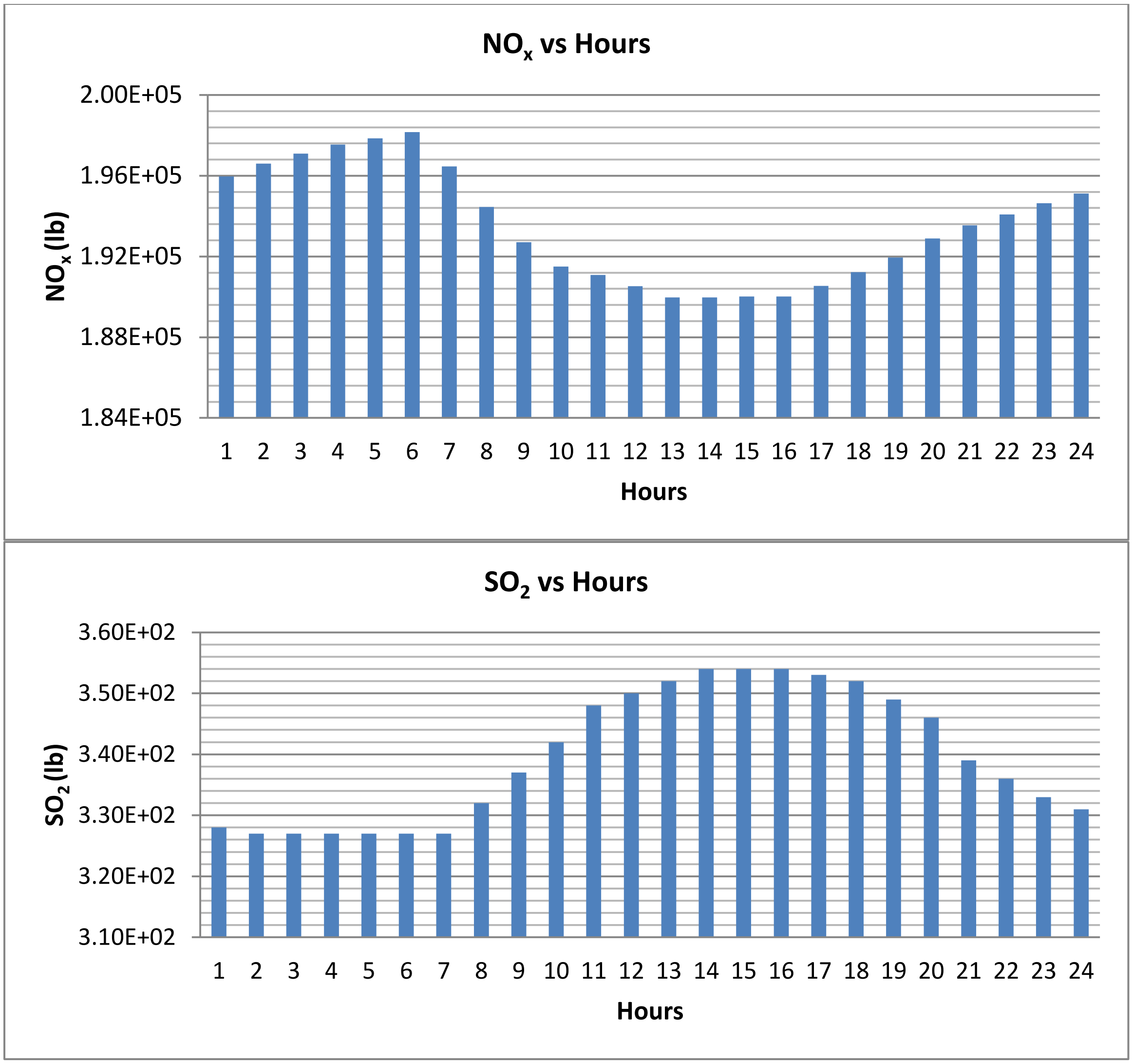
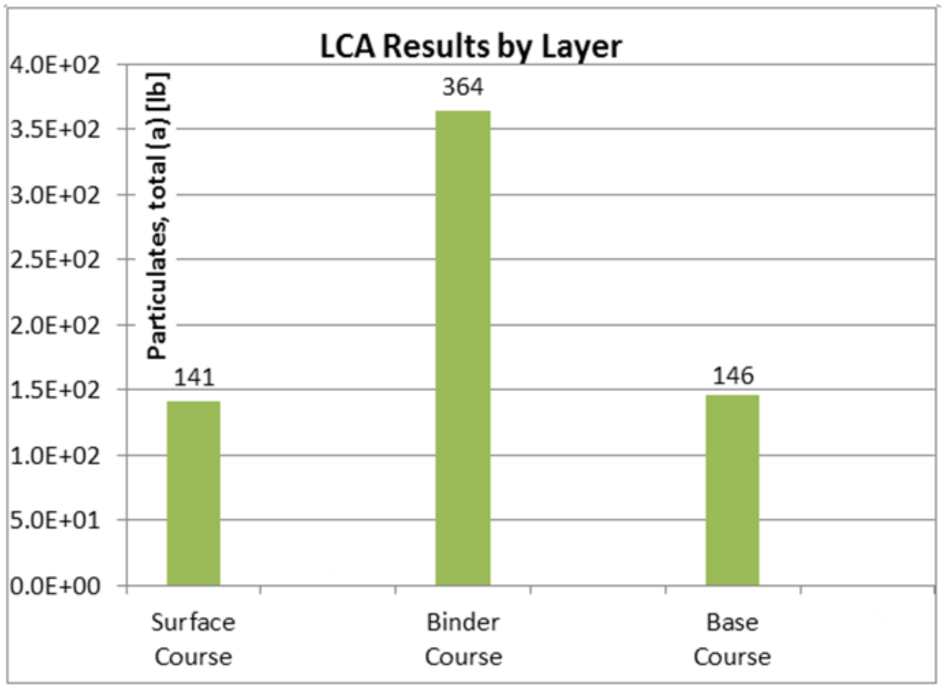


Figure C.2 Hourly variations of NO_x and SO_2

APPENDIX D

PM10 and VOC emissions of a case study using the LCA tool



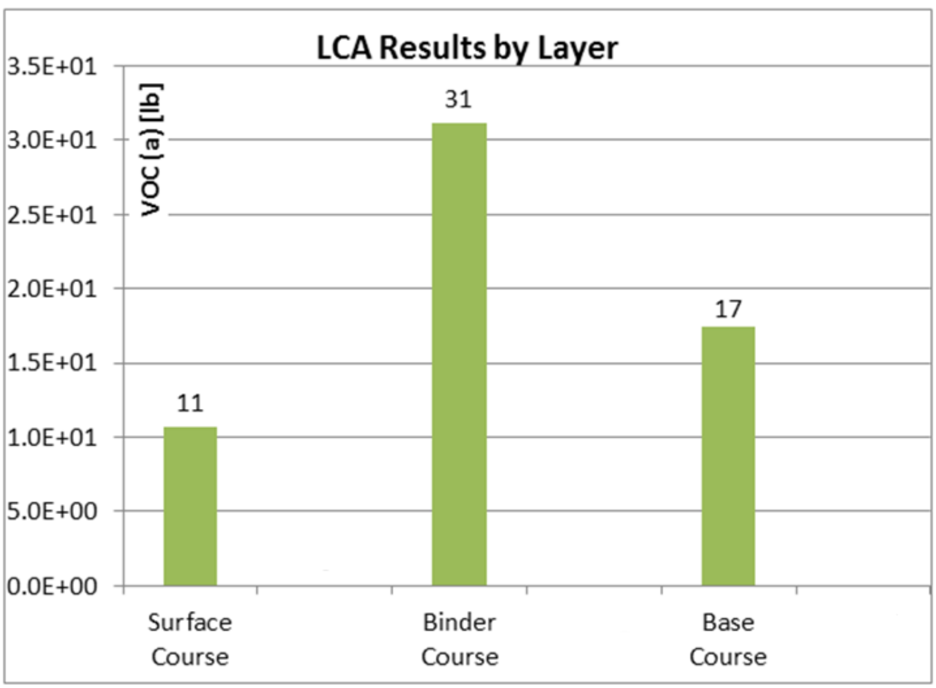


Figure D.1 Particulate matter (top) and volatile organic compound (bottom) emissions by pavement layer per one lane-mile of a flexible pavement on I-90