

**ENVIRONMENTAL LIFE-CYCLE ASSESSMENT OF HIGHWAY
CONSTRUCTION PROJECTS**

A Thesis

by

NEETHI RAJAGOPALAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2007

Major Subject: Civil Engineering

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Approved by:

Chair of Committee, Seth Guikema
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ABSTRACT

Environmental Life-cycle Assessment of Highway Construction Projects. (August 2007)

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Chair of Advisory Committee: Dr. Seth Guikema

Life-cycle inventory assessment (LCIA) provides us with quantity estimates of the inputs and outputs from a system. There have been limited applications of life-cycle assessment (LCA) to road construction in the United States. This thesis presents a life-cycle inventory of the environmental emissions to air from the construction of 3.2 miles (four lanes of highway) of a road in Texas. A process-based approach, which is basically a material and energy balance approach, was used and compared with the economic input-output life-cycle assessment (EIO LCA) method. The EIO LCA provides environmental emissions on the basis of a dollar value of a product or service used. A hybrid method was also employed to quantify emissions from the road. This hybrid method is an extension of the EIO LCA and is a recently developed method. Five major airborne emissions such as CO₂, CO, NO_x, SO₂, and PM were quantified but the comparisons with other methods were done using CO₂ as it had the highest value in emissions. The results of the process-based approach revealed that 18,590 tons of CO₂ were released to the environment, while the EIO LCA approach provided an estimate of 750 tons of CO₂ released. This thesis highlights the weak points of both methods and makes suggestions to improve both. Sensitivity analysis provides an estimate of the impact of different input values on the output. The results show that the emission factors utilized for calculating emissions affect the output the most. This research, by conducting an inventory assessment on a case study and comparing it with other methods, has shown that though the EIO LCA is a widely accepted method, the results provided are not always accurate. For individual cases, a combination of a process-based approach and an EIO LCA needs to be adopted.

To my parents and sister, Shruti, who stood by me always

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TABLE OF CONTENTS

	Page
ABSTRACT	iii
DEDICATION	iv
ACKNOWLEDGEMENTS	v
TABLE OF CONTENTS	vi
LIST OF FIGURES.....	ix
LIST OF TABLES	x
CHAPTER I INTRODUCTION	1
1.1 Background on LCA	1
1.1.1 Scoping.....	2
1.1.2 Inventory Analysis	3
1.1.3 Impact Analysis.....	4
1.1.4 Improvement Analysis	5
1.2 Atmospheric Emissions.....	5
1.3 Objective of This Research	8
CHAPTER II LITERATURE REVIEW.....	9
2.1 LCA for Products	9
2.2 LCA for Buildings.....	9
2.3 LCA for Construction Materials	12
2.4 LCA for Roads	17
CHAPTER III AREA OF INTEREST	20
3.1 Scope of Study	20
CHAPTER IV PROCESS-BASED APPROACH	23
4.1 Steps for an LCA.....	23
4.2 Boundary of LCA.....	23
4.3 Methodology	24
4.4 AP-42 Emission Factors.....	25
4.4.1 Emission Factors for Portland Cement Manufacturing.....	25
4.4.2 Emission Factors for Asphalt	27
4.4.3 Emission Factors for Lime Manufacturing	28

	Page
4.4.4 Emission Factors for Sand and Gravel Processing.....	29
4.5 Emission Factors for Transportation of Materials by Trucks	31
4.5.1 Running MOBILE 6.....	32
4.5.2 Creating Input File	33
4.5.3 MOBILE 6 Outputs	33
4.5.4 Program Availability	33
4.6 Emission Factors for Locomotives.....	37
4.7 Emission Factors for Machinery	38
4.7.1 NONROAD Program	38
4.8 Equipment Descriptions	40
4.8.1 Excavators	40
4.8.2 Asphalt Pavers.....	41
4.8.3 Compaction Equipment.....	41
4.8.4 Bull Dozers.....	42
4.8.5 Scrapers	43
4.8.6 Loaders	43
4.9 Results Tables	43
 CHAPTER V ECONOMIC INPUT-OUTPUT APPROACH	 46
5.1 Introduction of EIOLCA Concept.....	46
5.2 Environmental Impacts Addressed.....	47
5.3 Procedure for EIOLCA	48
5.4 EIOLCA	48
5.5 EIOLCA-Hybrid Approach.....	49
 CHAPTER VI SENSITIVITY ANALYSIS	 52
6.1 Introduction	52
6.2 Tornado Diagrams.....	52
6.3 Sensitivity Analysis Using TopRank	53
6.4 Sensitivity Analysis for Case Study	54
6.4.1 Sensitivity Analysis for Manufacture of Materials	54
6.4.2 Sensitivity Analysis for Transportation of Materials by Trucks	56
6.4.3 Sensitivity Analysis for Locomotives	58
 CHAPTER VII SUMMARY AND DISCUSSION	 62
7.1 Summary	62
7.2 Discussion	64
 REFERENCES.....	 66
 APPENDIX A EMISSIONS CALCULATIONS	 69

	Page
A.1 Manufacturing of Materials.....	69
A.1.1 Lime.....	69
A.1.2 Asphalt.....	69
A.1.3 Aggregates.....	70
A.2 Emissions from Transportation of Materials.....	71
A.2.1 Truck Emissions	71
A.2.2 Methodology for Calculating Locomotive Emissions.....	71
A.3 Emissions from Machinery Used	71
A.3.1 Production of Asphalt Paver-	72
A.3.2 Production of Bull Dozer-	72
A.3.3 Production of Scraper-.....	72
A.3.4 Production of Track Loaders-.....	73
A.3.5 Production of Excavators-	73
A.3.6 Reclaimer Mixers-	73
A.3.7 Dual Drum Vibratory Asphalt Compactors-	74
APPENDIX B MOBILE6 INPUT FILE	76
VITA	78

LIST OF FIGURES

	Page
Figure 1: Location of SH 40.....	20
Figure 2: Cross-section of Hwy 40	22
Figure 3: Tornado Diagram for Manufacture of Materials	56
Figure 4: Tornado Diagram for Heavy Vehicles (Cold Temperature).....	57
Figure 5: Tornado Diagram for Heavy Vehicles (Hot Temperature).....	57
Figure 6: Tornado Diagram for Locomotives	58

LIST OF TABLES

	Page
Table 1: Emission Factors for Materials	30
Table 2: Emissions from Materials Manufacturing.....	31
Table 3 : Emissions from Heavy Duty Trucks (Cold Temperature).....	35
Table 4: Emissions from Heavy Duty Vehicles (Hot Temperature).....	36
Table 5: Emissions from Locomotives.....	38
Table 6: Emissions from Non Road Equipment.....	44
Table 7: Total Emissions from Process-Based Approach.....	45
Table 8: Emissions from EIOLCA Approach.....	49
Table 9: Emissions from EIOLCA-hybrid Approach	50
Table 10: Upper and Lower Bounds of Emission Factors	55
Table 11: Upper and Lower Bounds of Emissions	59
Table 12: Relative Percentage Differences between Methods.....	62

CHAPTER I

INTRODUCTION

1.1 Background on LCA

Over the years, environmental issues have gained a lot of public attention. People have become more aware that the consumption of products and the services rendered have an impact at each stage to the natural resources. Due to the increasing awareness, the public and private sectors have started taking a keen interest in reducing the adverse effects, and in evolving methods for prevention of these impacts. In particular, sustainable development is becoming the goal for a lot of countries. Sustainability is defined by the United States Environmental Protection Agency (USEPA) as “...the ability to continue achieving economic prosperity while protecting the natural systems of the planet and providing a high quality of life for its people” (EPA 2007). The Brundtland Report defines sustainability as development which meets the need of the present without compromising the ability of future generations to meet their own needs (WCED 1987).

Sustainability of construction projects is becoming a key concern. The highway departments of various states have included sustainability in their vision statements. One of the vision statements of Texas Department of Transportation (TxDOT) is to provide safe, durable, cost-effective, environmentally sensitive and aesthetically appealing transportation systems that work together. There is no standard definition for transportation system sustainability, and it is generally defined through the system’s impact on the economy, the environment and general social well being; and measured by system effectiveness and efficiency and the system impacts on the environment (Jeon & Amekudzi 2005).

This thesis follows the style of *Journal of Infrastructure Systems*.

Addressing sustainability questions will be important for practitioners to incorporate sustainability into policymaking and will also help the decision makers of various government agencies to implement their vision statements. Life-cycle assessment is one tool that can be used for evaluating the adverse impacts our actions have caused to the environment and the society, thus providing for sustainability in our actions. According to the EPA, Life-cycle inventory is a “snapshot” of inputs to and outputs from the system (Vignon et al., 1994). It is used as a technical tool to identify and evaluate the environmental effects associated with a product or its production process over its lifetime. A life-cycle assessment has three major components-

- Inventory Analysis
- Impact Analysis
- Improvement Analysis

Some practitioners divide the LCA into four components with scoping being the first activity. Sometimes scoping is an activity which is included along with the inventory assessment stage. In this thesis, scoping is combined with the inventory assessment and is not considered a separate component. This method is commonly called the process-based approach.

1.1.1 Scoping

This activity is the first which is conducted in any life-cycle assessment. Scoping helps define the product or activity in the context in which the life-cycle assessment is conducted. This procedure helps define the extent to which a life-cycle assessment needs to be conducted. Typically, before starting an LCA, the purpose for which the assessment is being conducted must be defined as such a study is conducted in response to a specific question. The goals and boundaries of the study are set based on the question asked. For simplifying an LCA process, some steps can be excluded from a study, the general rule being, the conclusions of the study should not be affected. To make inferences about whether excluding a step affects the study or not, preliminary research needs to be done to understand the potential impact of each step. Good practice

for an LCA study is to enumerate all the steps excluded and to explain the reasoning for exclusion of specific steps. This allows for better utilization and understanding of the study for further related work (Curran 1996).

1.1.2 Inventory Analysis

Life-cycle inventory analysis began in the 1960s fueled by concern over increasing scarcity of raw materials and energy resources and uncertainty in ways to predict the cumulative energy sources available for future. The current method of analysis is based on the method started by the Coca-Cola Company to compare different beverage containers to determine which material had the lowest releases to the environment and used the minimum resources. Life-cycle inventory has evolved over the years and has been used to study a variety of consumer products (Vignon et al., 1994)

Inventory analysis is a quantitative data-based process which quantifies the energy and raw material requirements, and the various emissions to the atmosphere for the lifetime of a product or an activity (Vignon et al., 1994). The key concepts in conducting a life-cycle inventory analysis (LCI) are material and energy balances of the system in consideration. The basic steps for any LCI follows the steps: defining scope and boundaries, data collection, creating a computer model, analysis of results and final interpretation and conclusion. Depending on the bounds set for the analysis, each inventory will range from extraction of raw materials to disposal of the finished product. The boundary conditions needed to be clearly stated to identify the outputs from the inventory analysis stage. Assumptions about data are an inherent part of any analysis and assumptions are made because of lack of data in certain areas. The outputs finally obtained are consistent with the boundary conditions selected and the assumptions made about the data.

1.1.3 Impact Analysis

This component of a life-cycle analysis assesses the effects of the emissions and the implications of the raw materials usage quantified in the inventory stage. There is no fixed methodology for impact assessment developed as in the inventory assessment phase, by the Society of Environmental Technology and Chemistry (SETAC) and Carnegie-Mellon University's Green Design Initiative. The inventory phase of an LCA produces a long list of resources used and release to the environment. It is very difficult to interpret based on the results whether one product or process is better than the next. An impact assessment converts the results obtained from an LCI into impact measures such as mortality rate, disruption of habitat etc. that helps in interpreting the total environmental effects of the system (Curran 1996). A conversion factor such as a multiplier could be used to link the LCI outputs to some impact categories. An example could be development of acid rain potential for various air emissions. No accepted methodology is available due to lack of adequate data but there is high level of interest in conducting an impact assessment.

A conceptual framework is presented for impact assessment consisting of: classification, characterization and valuation. Classification, the first step is the process of assigning inventory results into specific categories such as environment and ecosystem quality, quality of human life, natural resource utilization and social welfare. Some of the major ecological impact categories are global warming, ozone depletion, acid rain, weather alterations. The human health impact categories include human carcinogens, effects to respiratory central nervous, cardiovascular and reproductive systems. Characterization, the second step assesses the magnitude of the impacts on the chosen categories and the last step, valuation assigns relative weights to the different impacts. After the completion of the valuation step, the overall impact can be directly compared.

1.1.4 Improvement Analysis

This part looks at various ways to reduce the environmental burdens associated with an activity. Both quantitative and qualitative measures of improvement are discussed for this component. This component is not well developed and is not widely discussed (Vignon et al 1994).

1.2 Atmospheric Emissions

An LCI report for environmental releases should be considered as some form of impact assessment. The listing of releases implies that the emissions have a detrimental effect on the environment but no attempt has been made to analyze the nature of the environmental effects (Curran 1996). Since the inventory assessment just quantifies the environmental emissions, the environmental releases and their quantities are known but to mitigate the effect of these releases further actions need to be taken such as an impact analysis.

A life-cycle inventory analysis quantifies five types of output- airborne wastes, waterborne wastes, solid wastes, products and co-products (Ciambrone 1997). Typical atmospheric emissions of concern are

- Carbon dioxide (CO₂) – Carbon dioxide is released to the atmosphere by the burning of fossil fuels, solid waste, trees and also through some chemical reactions. CO₂ is an important greenhouse gas which is increasing the climate changes occurring in the world at a rapid rate due to its accumulation in the atmosphere. CO₂ has a global warming potential (GWP) of 1.0. GWP is the comparison of ability of different greenhouse gases to trap heat in the atmosphere. The GWP helps in converting emissions of various gases into a common measure which allows for aggregating the impacts of various gases in carbon or CO₂ equivalents (IPCC 2002). CO₂ and water vapor are normal by-products of combustion of fossil fuels and the one of the solutions to reduce CO₂

in the atmosphere is to decrease the consumption of fossil fuels. Another solution can be to sequester the CO₂ emitted into oceans and trees (Ciambrone 1997).

- Nitrogen oxides (NO_x) - A group of gases containing nitrogen and oxygen in varying degrees are collectively called nitrogen oxides (NO_x). It has both natural and manmade sources. Manmade sources are those utilities or vehicles that burn fuel at high combustion temperatures. The chief concern is that it aids in formation of ozone by combining with hydrocarbons in the presence of sunlight and is a contributor to smog formation and global warming (Ciambrone 1997).
- Sulfur oxides (SO_x) - Gases containing sulfur and oxygen are collectively called sulfur oxides (SO_x). Sulfur oxides are formed when fuel containing sulfur such as coal or oil is burned or when gasoline is extracted. They dissolve easily and are a major environmental and health concern. These emissions are reduced only by usage of fuels containing low amounts of sulfur or by switching to non-combustion energy sources (Ciambrone 1997).
- Carbon monoxide (CO) - A colorless, odorless gas formed when fuel is not burned completely and is released mostly from vehicles exhaust. The main reason for concern is that it causes serious health problems (Ciambrone 1997).
- Volatile organic compounds (VOC) – These are a group emitted as gases from certain solids and liquids. These include a wide range of carbon-based molecules such as aldehydes, ketones and hydrocarbons which participate in an atmospheric photochemical reaction but exclude carbon dioxide, carbon monoxide, carbonic acid. They contain various chemicals which may cause serious health effects (Ciambrone 1997). VOCs include a wide array of chemicals, some of which may have short-term or long-term health effects. Some of the sources of VOCs are paints, wood preservatives, cleansers and disinfectants, air fresheners, automotive products.
- Particulate matter (PM) - This is a complex mixture of very small particles. The size of the particles is directly related to the health problems which can occur. EPA is concerned about small particles of 10 micrometers or less in size as they

cause major health problems. PM is generally a residue of combustion of unburned fuel and lubrication oil. NO_x and PM emissions are interdependent because the technology used to reduce NO_x generates high PM. Similarly PM controlling technologies also produce high quantities of NO_x. Due to advanced filtration techniques, the PM that is now present is mostly in the order of 2.5 microns or in the form of PM_{2.5} (Ciambrone 1997).

The EPA has targeted these emissions and is trying to reduce the emissions of these for various health and climate-protecting reasons. To quantify these emissions, the best method available is a life-cycle assessment.

An inventory analysis, when done, is beneficial for an overview of the environmental assessment and the relative contributions from each stage of a process. It is also useful in public policy decisions in the sense that a policy-maker takes into account the results of an inventory in making policy decisions.

Life-cycle assessment is evolving slowly to be used effectively in infrastructure. As will be revealed in the literature review, life-cycle assessment is used as an important tool for assessing environmental emissions from buildings. Based on the actual framework of how an LCA is conducted, life-cycle assessment for infrastructure is broken down into its constituent phases. Life cycle assessment of a highway is done in three stages. The lifetime of the road is broken down into three constituent phases (Park et al. 2003) -

The construction phase

The operation and maintenance phase

Final disposal phase

Another method commonly used for performing an LCA is an Economic Input-Output Life-Cycle Assessment (EIO-LCA) developed by the Carnegie-Mellon University's (CMU) Green Design Initiative. Chapter V in this thesis is dedicated to explaining about

this approach. Both the process-based approach and the EIOLCA are used as a comparison basis for the results.

The literature available on LCA for products shows that though LCA has been used as a tool for estimating the environmental releases. The LCA used for infrastructure looks into environmental releases from structures which do not exist but are made up by the researchers. This research aims to do an LCI for a project which is actually constructed and quantify emissions from it.

1.3 Objective of This Research

The objective of this research is to compare the results from three approaches for an inventory assessment conducted on a case study. This research tries to show, with the help of the case study, that the widely accepted method, the EIOLCA cannot be used generically for every situation. An estimate of the environmental emissions can be obtained using the EIOLCA, but for a greater degree of accuracy, a combination of a process-based approach and an EIOLCA would help. Though this study conducts an inventory assessment of a case study, the research contribution lies in the fact that the comparison of the three approaches prove that both the process-based approach and EIOLCA do not give similar results in all situations. For a general estimate of environmental emissions, the EIOLCA is a useful tool but for case-specific emissions, a process-based approach will provide better results.

CHAPTER II

LITERATURE REVIEW

2.1 LCA for Products

The Society for Environmental Toxicology and Chemistry (SETAC) along with EPA has played a major role in standardizing LCA. A workshop held by SETAC in 1990 helped define terms for describing the LCA concept. This workshop helped in the realization that life-cycle inventory assessment is more developed than impact assessment method and so is more often used (Curran 1996). The SETAC based approach is called a process-based approach and most initial studies used this approach. The first major life-cycle assessment was conducted on beverage containers in 1969. This assessment was initiated by the Coca-Cola Company to analyze the impact of the containers on the environment. The objective of the research was to identify the type of container with a least impact on the environment. Similar studies were initiated in the US and Europe in the 1970s. Studies were conducted which tried to identify the benefits of paper over plastic bags. The entire life cycle from raw materials processing to disposal and recycling was considered. The environmental impact of semiconductors was also analyzed (Ciambrone 1997). The recommendations for the semiconductors involved change in the chemicals used for manufacture, reduction in the chemicals and lowering the energy consumption (Ciambrone 1997).

2.2 LCA for Buildings

The life-cycle assessment concept has been extended to buildings as well. A study was conducted using the LCA approach for a new high-end office building in South Finland (Junnila et al 2003). The energy use and emissions from the life-cycle of the office building was assessed assuming fifty years as its service life. This study conducted an inventory as well as impact assessment on the office building as given in the process-

based approach formed by SETAC. For the inventory analysis phase, materials and energy balances of the building were obtained from drawings and specifications used while constructing the building. The inputs and output from the building (the material and energy flows) were identified during the construction phase of the building itself. Emissions data was obtained from the manufacturers involved in the actual construction. The data missing was the heavy metal emissions from transportation and use of construction machinery. The phases considered for the inventory assessment were – manufacturing of building materials, construction, use, maintenance and demolition. Transportation of materials was not a separate phase but was included in each of the above five phases. Data was obtained for each of these phases either from the specifications or from the standards given by the Finnish government. Impact analysis for the study identified four major categories as climate change, acidification, eutrophication and dispersion of harmful substances. To obtain a ranking for the various services in a building, their environmental impacts are compared. The results obtained showed that the structural systems and HVAC systems had the maximum impact on the environment. The construction activities only account for 3-11% of the total impacts. Energy consumption (heat and electricity) is the most important activity in a life-cycle in other studies as it accounts for nearly 80-90% of climate change. The results of this study concluded that the energy consumption accounts for 60-75% of climate change in an LCA.

Though only a case study of one building, the work of Junnilla et al (2003) provides a useful reference for energy consumption of office buildings in Finland. The practical aspects of this study are that more environmentally-conscious design can be made but further studies have to be conducted to standardize the results of this study in countries in a different geographic location such as the US. Also, a sensitivity analysis would have been more effective in explaining the uncertainties related to the research. Further studies can benchmark their environmental performance against the case study presented in this research.

Another study which focused on comparison of energy use and environmental emissions from office buildings in the US and Europe was conducted (Junnila et al. 2006). The study was conducted for the entire life-cycle of 50 years. The objective was to identify the most energy-intensive phase in the life-cycle of an office building and to promote environment-friendly practices for buildings. The study focuses only on the inventory analysis stage of LCA. Two office buildings, one in Southern Finland and one in the Midwestern US are selected for their life-cycle use of fifty years.

The European building's emission data is collected from actual sources and material providers in Finland. Materials and energy flows are obtained from design and construction plans used for construction of the office building. For the office building located in US, the material emissions data and the supply chain effects are obtained by using the EIOLCA approach. A process-based approach as given by SETAC is used for all phases except for the materials manufacturing, machinery, and electricity components. For the excluded phases and supply chain effects, EIOLCA approach is used. This approach was developed by the Carnegie-Mellon University and provides an estimate of environmental emissions as output based on a dollar value of use of a component. It uses the Department of Commerce's commodity-commodity input-output matrix.

The phases chosen for both locations include materials, construction, use phase and maintenance. In the European case study, it was found that the use phase dominates in emissions, contributing nearly 50-90% of the total emissions. The next most important phases are materials and maintenance, particularly for the PM₁₀ emissions. The life-cycle phases are further divided into life-cycle elements like electricity and heating which were estimated to cause 30-45% of overall emissions. All other life-cycle elements produce fewer emissions.

In the US study, though the use phase is a major contributor to PM₁₀ emissions, the materials and maintenance phase have the most significant impact. Where the use phase has an impact of 46% in all categories of emissions such as CO₂, SO₂, NO_x and energy use, of the life-cycle, the materials and maintenance phase have at least 22% in each of these categories in a life-cycle. Construction and end-of-life phases have less impact.

Though the buildings are in different geographic locations, the proportion of emissions from the different life-cycles is similar. Though the use-phase dominates in PM₁₀ emissions, the maintenance phase has a higher environmental burden than the materials and construction phase. Overall, the Finnish building emits a third of the CO₂ and uses half the energy of the US building. The differences could be because of the difference in the energy mix. Where Finland uses combined heat and power, using 67% natural gas, 32% coal, 0.2% oil and 0.3% biogas, the US uses an electricity mix of 40% petroleum, 21% coal, 22% natural gas, 7% nuclear, 5% hydropower and 5% wood and waste and 0.1% geothermal, wind and solar energy. Knowing the life-cycle emissions from current buildings will help in making more environmentally-friendly designs in the future.

This study on comparison of energy consumption in Europe and the US gives us a picture of the impact of the various phases on the environment. Though both the countries use the same technology for construction as well as use, the emissions are different for the office building because of the difference in the energy mix. Similar results may be expected from other infrastructure such as roads where the materials used differ from region to region within a country itself.

2.3 LCA for Construction Materials

Life-cycle assessment techniques have also been employed to study the environmental implications of construction materials (Horvath 1997). As one of its main goals, Horvath's thesis looks at the environmental implications of alternate product choices:

asphalt versus reinforced concrete pavements, steel versus reinforced concrete bridge girders, and wood versus steel framing. This study shows that for roads, asphalt is a better material than concrete in the manufacturing and end of life stage whereas concrete is a better option in the use stage. For girders, concrete is a much better material in the manufacturing and use phase but steel has the advantage of recyclability in the end of life phase. For framing, it was found that though wood is a much better material in terms of environmental load in manufacturing phase, steel has the advantage of recycling. Horvath (1997) utilizes the EIOLCA approach for all of the comparisons. The objective of the above study was to provide comprehensive metrics for construction materials selection and for design selection which would help those in the construction industry as well as in academia to make environmentally sound decisions.

In the study conducted by Horvath (1997), the environmental impacts associated with the construction materials used are quantified. The energy consumption of construction materials from their manufacture to their disposal phase is quantified using the process-based approach and the results compared to the EIOLCA approach for embodied energy from each material. The energy used in the mining, production and transportation of materials is defined as embodied energy. The embodied energy data is available for certain materials in literature. But, there is uncertainty based on data, unavailability of data for many of the materials, an ambiguous boundary for analysis of data, and use of technology which might be outdated for the manufacturing of the particular materials. So, comparison of values obtained from the process-based approach with the EIOLCA approach is not possible for certain embodied energy of materials due to limitations in the EIOLCA process.

Horvath (1997) used EIOLCA to provide energy values for fuel types used in the manufacturing of materials, and the production or transportation of materials. For ease of comparison, each of the outputs for the energy of the fuel types is given in mega joules (MJ). The electricity consumption of each of the materials and the conventional air

pollutants released is also given by the EIOLCA. The uncertainties associated with the data in both the SETAC approach and EIOLCA approach have not been addressed through statistical analysis. A qualitative measurement of the data used for EIOLCA is conducted.

To illustrate the environmental impacts of construction materials in Horvath (1995), three case studies are conducted. For the three case studies, equivalent performance was assumed, i.e., any material used for the structure behaves in the same manner. For the manufacturing stage, EIOLCA approach is used and for the environmental data, SETAC approach is used. Comparison of the materials was done based on their environmental burden. Based on the study conducting a comparison between asphalt and reinforced concrete pavements, it was found that it was difficult to conclude on the better of two on environmental grounds. The average life of the road varies depending on the place where the road is situated and maintenance requirements and cost vary from place to place. But based on the LCA performed, asphalt pavements were found to be more environmentally friendly in the materials extraction and materials stage and are also widely recycled. Concrete, though more environmentally friendly, is not recycled. Steel has the advantage of recycling over concrete. Similarly, in the case of wood and steel framing, wood has a lower environmental burden but steel can be recycled.

The study used the EIOLCA approach for comparison of construction materials. This was one of the achievements. But though, comparisons were made, the results do not help in taking environmentally-sound decisions. Future suggestions for comparisons of various other construction materials were also given. Overall, the study showed that various design factors have to be taken into consideration before deciding on a material. Environmental factors alone are not enough in deciding on a material for construction.

Comparison of the best material to use for bridges in terms of environmental implications has also been carried out by Horvath et al. (1998) and Keoleian et al.

(2005). The study conducted in 1998 is a part of Horvath (1997). The study examines the best material to be used for bridges in terms of reinforced concrete or steel. This study shows that for the construction phase of the bridge, concrete has a lower environmental burden but the possibility of reuse and recycling of steel make it a much better option in bridges. For individual cases, all factors such as economic criteria, aesthetics, environmental factors and design factors need to be considered before deciding on a material to be used for construction. Keoleian et al. (2005) conducted an LCA on bridge decks using conventional concrete in one method and engineered cementitious composites (ECC) in another. Alternative materials need to be found so that the undesirable properties of concrete such as brittleness can be overcome. A holistic approach like LCA needs to be conducted to quantify the environmental impacts from materials for the selection of construction materials. Where Horvath et al. (1998) used EIOLCA approach, Keoleian et al. (2005) uses the process-based approach to evaluate a bridge made of conventional steel joints and an alternative steel design constructed with ECC. Life-cycle inventory (LCI) of the bridge system is carried out in accordance with ISO standards. The study is conducted to highlight the capability of LCA and not to determine the better of two materials. The stages considered for LCA are the manufacturing stage, construction, use, and end of life management stages related to bridge repairs. The data for the manufacturing phase is obtained from various sources such as the Portland Cement Association and International Iron and Steel Institute, the construction machinery emissions are obtained from NONROAD; automobile emissions are obtained from MOBILE 6.2. The traffic on the road is also estimated and LCA emissions quantified for a period of 60 years service life. This study shows that the ECC can be used for limited applications to enhance environmental performance. This study goes a step further from similar studies by incorporating the various construction processes which go on in a bridge over its entire service life. The study shows that these construction phases contribute significantly to the total life-cycle impacts and the frequency of construction and maintenance affect the environmental impacts. The major assumption made is that ECC has a service life twice that of conventional systems.

Further studies have to be conducted to test ECC on an actual bridge deck. To evaluate alternate materials for any system, the main points to be noticed are the maintenance and repair schedules. The results show that the materials acquisition and processing phase is the second largest in the total life-cycle burdens in categories such as energy consumption and global warming. Criteria for selecting materials need to be refined to provide for improved sustainability in infrastructure.

Another study which estimated the energy consumption of materials used for a road segment was conducted (Zapata et al 2005). A 1 km two lane segment of road in the United States is assumed to be the base of the study. The materials used for comparison are asphalt and Portland Cement Concrete (PCC). This study used the process-based approach for its analysis. An inventory assessment of the energy consumption of the different materials is the goal of this research. For comparison with a similar study conducted by Horvath et al. (1998) the pavement design was assumed to be designed according to AASHTO guidelines, yielding equivalent designs and functionality. The inventory assessment was conducted for the following steps – manufacturing of raw materials, construction, use, maintenance and repair and recycling and disposal of the road. Due to lack of data, the Zapata et al. (2005) study is limited until the construction phase only. The conclusions of this study were that concrete imparts higher energy in the first three phases (extraction, manufacturing, and placing the material on the construction site) whereas asphalt requires lesser energy in these phases for the same service life. Also, concrete and steel are not recycled as often as asphalt. This contributes to a higher energy impact of concrete. Cement is the major energy consumer in concrete pavements whereas the drying of aggregates consumes maximum energy in asphalt pavements. Life-cycle assessment can be used by many of the companies to understand the environmental effects of their current manufacturing technologies and the results obtained after an assessment can be used for providing better environmentally-friendly solutions.

2.4 LCA for Roads

Life-cycle assessment for highways has been done in very few places. A thesis written in Sweden (Stripple, 2001) focuses on estimating the emissions from the life-cycle of all phases starting from extraction of raw materials to the final repair and maintenance stage for a 1 km stretch of hypothetical road. This work concentrates only on the inventory assessment of a life-cycle of a road. The service life of the road is taken as 40 years. This is the first study which uses a detailed LCA technique to investigate the road construction processes for an asphalt road as well as a concrete road. The entire production process is broken down into sub components which are each analyzed separately using the LCA technique. Examples of the components included are electricity consumption and emissions and energy consumption during transport by truck. The thesis concludes that the emissions of NO_x, SO₂, and CO₂ are higher in the construction stage of the road than the other stages in an inventory assessment. The total energy consumption during construction, operation and maintenance of 1 km of the stretch of road during the 40 years period is found to be 23 TJ for asphalt roads and 27TJ for concrete roads. The difference is because of the consumption of coal for manufacturing cement. The results will be suitable for a road constructed in a similar geographic location with comparable data. Due to differences in energy consumption between the US and Europe, the same results cannot be applied for a road construction in the US. This result justifies the construction stage inventory of assessments in the inventory assessment for our research as the construction phase is the major energy consumer in the life-cycle of a road.

Subsequent papers also adopted the same functional unit of 1 km road as assumed in Stripple (2001). Park et al. (2003) were the first to conduct a life-cycle inventory for an road. Park et al (2003) divided the life-cycle of a Korean case study road into four stages: manufacturing of construction materials, construction stage, maintenance and repair, demolition and recycling. Park et al. (2003) focused on a 1 km stretch of road in Korea as the functional unit (FU) and the environmental output to the air is given in tons

of oil equivalent (TOE). A ton of oil equivalent is the amount of energy released when one metric ton of crude oil is burned. This work was basically a process-based model. The manufacturing phase output is given using Input-Output tables from Korea. A regression model created showed that there is positive correlation between road span and energy consumption. This means that as road span increases, energy consumption increases along with it. Though each phase contributes towards the total energy figure of 2676.7 TOE/FU, the manufacturing phase has the maximum load. Though this paper provides us with a good background of how a life-cycle technique is adopted for an road segment, the paper does not incorporate the supply-chain effects of a construction activity. The previous work done on ELCA provides us with a good background to start but it does not adequately address the complexity and size of construction for a road that is constructed. Also, this study is in a different geographic location and the results do not apply to the US again.

The various studies conducted show how LCA is a holistic approach to understand the environmental emissions from any infrastructure. Solutions ranging from the more environmentally friendly material of two construction materials to the atmospheric emissions from a road can be obtained by conducting an LCA. Most of the studies used either the process-based approach or the EIOLCA to estimate the environmental emissions on hypothetical structures. The previous studies provide guidance for this research to conduct an LCA on a road. The methodology adopted by previous literature is adopted for this study also. This study goes one step further by conducting a life-cycle inventory assessment on a case-study. Though an LCIA framework as adopted by similar studies is used, the assumptions made for this study vary according to the data available.

The results obtained in a process-based approach in the case-study are compared with the EIOLCA method. The comparison shows the difference in results obtained from both the methods. Though the case study provides us with quantities of emissions, it was only

after the comparison it was found which method provides results which can be approximated to the actual emissions to air. It is important to compare the results from all methods available so as to obtain the most accurate estimate of the emissions from construction of a road. The research contribution lies in the fact that an inventory assessment of a road was conducted and the results were compared using three methods- each method giving different results. The difference in results is observed at the comparison stage. This research has conducted an inventory assessment of a road using a process-based approach but this study goes one step ahead by comparing the results from three methods and analyzing the reasons for the difference.

CHAPTER III

AREA OF INTEREST

3.1 Scope of Study

One of the objectives of this research is to conduct an LCI on a road segment in the US and to quantify emissions from the road segment. The main objective is to compare the results obtained from the LCI or road using a process-based approach to the EIOLCA. Reasons for the difference in results will be sought. The road segment selected is State Highway 40 located in College Station, Texas constructed by Texas Department of Transportation (TxDOT). The total length of the road is 3.2 miles having a width of 100 feet (four-lane highways) including curbs and gutters. The SH 40 is a feeder road which connects FM 2154 to SH 6 which runs all the way to Houston, Texas (Fig 1). The actual value of the work is \$6,810,725.



Figure 1: Location of SH 40

Every highway construction has an environmental impact statement (EIS) written which shows the impact the construction of the road will have on the environment. Highway 40 has a document called the Biological Opinion which shows the impact the construction of this road has on areas surrounding the land used for the road (USDI 2003). This states that the proposed area for SH 40 has a large number of native trees called Navasota ladies'-tresses. Ten of these trees were identified in a 32-acre area proposed for construction of the road. Of these, six plants were to be affected and the remaining four which are in the SH40 Right Of Way, were not expected to be affected directly or indirectly by the construction. The ten plants represent 0.21% of the total 2,814 plants available in Texas. The project was expected to eliminate 0.21 acres of trees in College Station. The additional effects due to removal were changes in surface and subsurface hydrology. The cumulative effects include habitat loss in the region. The study arrived at the conclusion that the construction was not likely to affect the continued existence of Navasota ladies'-tresses.

The soil in Texas is clay soil. To stabilize the clay soil 10 inches of lime-treated sub base is placed and mixed in the clay sub grade. Over the lime base is 18 inches of granular base topped with 2 inches of hot mix as shown in Fig 2. Based on this information an LCA is performed on SH 40. The road was let out for construction in October 2003 and it opened to public in June 2006. The Bill of Quantities (BoQ) which is a document containing the quantities of material used in each work item for a road is obtained from TxDOT. The raw materials such as cement, RC pipes and lime are assumed to be transported from in and around Texas, specifically from Houston and Austin. High quality aggregate is scarce in Texas so it is assumed to be brought in from Wyoming by trains.

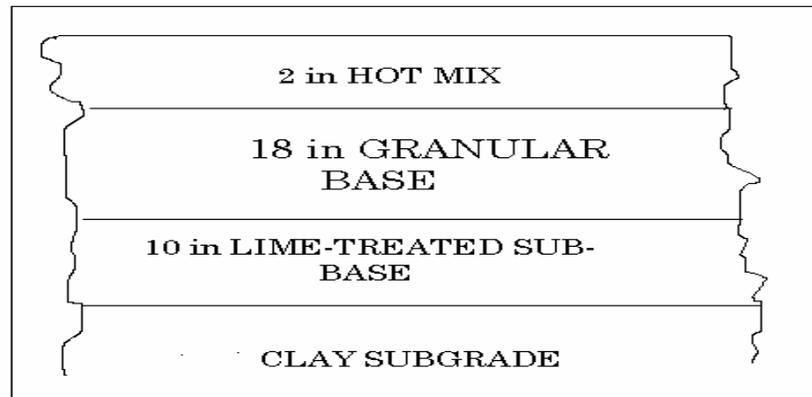


Figure 2: Cross-section of Hwy 40

CHAPTER IV

PROCESS-BASED APPROACH

4.1 Steps for an LCA

The LCA methodology as given by SETAC includes an inventory analysis, impact analysis and an improvement analysis. The inventory analysis stage is further divided into the phases- manufacturing of raw and construction materials, construction of road, use of road, maintenance, final disposal and recycling of road. Of these steps, the manufacturing of raw materials and construction of the road will be followed to quantify the emissions from 3.2 miles of SH 40 road in Texas.

4.2 Boundary of LCA

In this study, only the inventory analysis stage is included. There is insufficient data and literature available to do a good impact analysis. So impact analysis is not included in the scope of the study. The inventory analysis is also divided into various phases as stated before. For this study, only the manufacturing of materials and their use in construction is included. The construction phase includes the transportation of raw and construction materials and the usage of machinery during construction. The use, maintenance, and disposal phases are outside the scope of this study. To conduct a good inventory of the emissions from the use and maintenance phase, good equipments and data are necessary. Since obtaining these proved to be difficult, these were not included in the scope of this study. The emissions to air are considered. The other outputs such as only emissions to water and soil are not included due to lack of data.

4.3 Methodology

A Bill of Quantities (BoQ) is available from TxDOT for the asphalt concrete road construction. This document contains 110 line items of work. The entire document is divided on the basis of materials used and materials & equipment use. A preliminary sorting is done on a total amount basis, the highest amount first. The items of work which are below a three digit figure in amount are not included in the study because their value is considered to be too small in comparison with the whole project. The basic formula for calculating the emissions is the product of the quantity of material and the emission factors. Emission factors are representative values that try to link the quantity of pollutant released with the associated activity which releases it. In general, a road construction uses raw materials like sand, cement, asphalt, coarse aggregate is used. The BoQ provides us with values of the total quantity of the item, for example, 172,447 m³ of a lime treated sub grade. The volume of raw materials which make up the lime treated sub grade is not available in the BoQ. The constituent materials are then calculated by assuming standard values and reviewing literature. For e.g. for any concrete work item a ratio such as 1:1.5:3 is assumed for cement, sand and gravel. After obtaining the constituent materials volume for each work item, the emissions are calculated by the method already stated. For e.g. assuming the ratio as 1:1.5:3, if the cement, sand and gravel volumes are calculated as 100 Mg, 150 Mg and 300 Mg, the emission factors of the respective materials in kg/Mg is applied and the emissions obtained. Each of the phases has distinct emission factors obtained from various models developed by the EPA. These models will be explained in detail below. The emission factors are obtained from (US EPA 1995). Emission factors for the manufacture of materials like sand, gravel, lime, asphalt, cement are available from EPA (1995). For the transportation of materials, emission factors are obtained from a computer model developed by the US EPA called MOBILE 6 (US EPA 2006). For the machinery and equipment usage, a model called NONROAD (US EPA 2005) is used.

4.4 AP-42 Emission Factors

The US EPA's Office of Air Quality Planning and Standards (OAQPS) developed the AP-42 document to describe the procedures, technical standards and specifications for reporting air pollution emission factors (US EPA 1995). AP-42 was first published in 1972 and has undergone various revisions. The manufacturing process of each material and the source of airborne emissions from each material are described below.

4.4.1 Emission Factors for Portland Cement Manufacturing

Portland cement is a gray or white fine powder, which is essentially a mixture of hydraulic cement materials composed of calcium silicates, aluminates and aluminoferrites (EPA 1995). The materials which are used for manufacturing cement can be divided into four categories: calcareous, siliceous, argillaceous and ferriferous. The process of cement manufacturing can be divided into the components: raw materials acquisition and handling, kiln feed preparation, pyroprocessing and finished cement grinding.

Calcium is the main element of highest concentration in cement and it is obtained from a variety of sources like limestone, chalk, sea shells, aragonite and an impure limestone known as natural cement rock. The raw materials are generally obtained from open-faced quarries but other methods used are underground mines or dredging operations. Other raw materials included are silicon, aluminum and iron. These raw materials are obtained from ores such as sand, shale, clay and iron ore. These materials are also mined from open-pit quarries or mines but dredging and excavation from underground is also carried out.

The second step is the preparation of raw mix or kiln feed for pyroprocessing. The raw materials processing differ for the wet and dry processes. If dry kiln processing is used, the cement raw materials whose moisture content varies from 1 to 50 percent are dried to less than 1 percent moisture. The dry raw mix is pneumatically blended and is stored in

silos specially constructed for this purpose until they are used in the pyroprocessing process. In the wet process, water is added during grinding of raw materials thus producing slurry of approximately 65% solids. This slurry is stored in tanks until it is used in the pyroprocessing process.

The pyroprocessing process, the main part in the manufacture of cement, transforms the raw mix produced in the earlier step into clinkers, which are gray, glass-hard, spherically shaped nodules. Five different processes are used to achieve the pyroprocessing step: the wet process, the dry process (long dry process), the semidry process, the dry process with a preheater, and the dry process with a preheater/ precalciner. Each of these processes has the same physical and chemical processes required for manufacture of cement. The differences lie in equipment design, method of operation and fuel consumption.

Whichever pyroprocess is used, the last component is clinker cooling. This process recovers around 30 percent of heat which is input in the kiln, freezes mineralogy thus keeping the desirable qualities inside and makes it possible to handle the cooled clinker with conventional conveying equipment. The last step in manufacturing cement involves blending and grinding operations that help in converting the clinkers into cement.

In the manufacture of cement, the primary airborne emissions are particulate matter (PM), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO) and carbon dioxide (CO_2). Sources of PM include quarrying and crushing, storage of raw materials, the grinding and blending in the dry process. The largest source is the pyroprocessing system which has the kiln and clinker coolers. Emissions from kilns have been restricted to 0.15 kg/Mg and from clinkers to 0.050 kg/Mg PM

Nitrogen oxides are generated during fuel combustion. As flame temperature increases, the nitrogen oxides generated increases. Sulfur dioxide is generated from sulfur

compounds in fuel as well as sulfur compounds in the raw materials. The quantity of SO_2 released is reduced by its absorption due to the alkaline nature of cement. Depending on the process used for manufacture, the absorption rate varies from 70 percent to more than 95 percent. There are two mechanisms generating CO_2 in the manufacturing process- the first is the general combustion of fuel releasing CO_2 and the second is the calcining of limestone or other calcareous material. The range of CO_2 emissions from pyroprocessing generally falls in the range of 0.85 to 1.35 Mg of CO_2 per Mg of clinker. Smaller quantities of CO and VOC are released if combustion reactions do not reach completion. For this study, a wet process kiln is assumed to be used. A wet process kiln has the highest values of emission factors for CO_2 . The emission factors used are: CO_2 -1100, NO_x -3.7, SO_2 -4.1, CO-0.060 and TOC-0.014; all units are in kg/Mg. So the method is assumed to be used to give us a maximum estimate of emissions. The emission factors that are used are given in Table 1.

4.4.2 Emission Factors for Asphalt

Asphalt surfaces and pavements are made of aggregate and an asphalt binder. Aggregate materials are obtained from rock quarries or from natural gravel deposits. The function of the aggregate is to transfer load from surface to the base course, to take the wear and tear and provide a nonskid surface. The asphalt binder is provided to hold the aggregate together to prevent its displacement and also to provide a waterproof cover. Asphalt binders are available in two forms-asphalt cement and liquefied asphalt. Liquefied asphalts are further divided into cutback asphalt and asphalt emulsions. Cutback asphalt falls into three categories-rapid cure (RC), medium cure (MC) and slow cure (SC) oils. The primary pollutants are volatile organic compounds (VOC).

Hot mix asphalt is a mixture of aggregate and liquid asphalt cement. Hot mix asphalt materials are manufactured by batch mix plants, continuous flow mix plant, parallel flow drum mix and continuous flow drum mix plants. Batch mix plants have two categories of emissions: ducted emissions (emissions from vents and pipes) and fugitive sources

(emissions sent directly to air without vents or pipes). The significant source of ducted emissions is the rotary drum dryer and the dryer emissions consist of PM and products of combustion such as CO₂, NO_x, SO₂ and CO. The process starts with aggregate being hauled to the hoppers of the cold feed unit. From the hoppers, the material is transferred to the conveyor belt and is transported to a rotary dryer. From the dryer, the aggregate goes into a bucket elevator where it is graded into four different sizes and is dropped into hot bins according to their size. To achieve an appropriate aggregate-asphalt cement design, the asphalt cement is also simultaneously weighed. The major source of emission for PM is the rotary drum dryer. The emission factors used are based on the assumption that a batch mix plant is used in which a natural gas-fired dryer is used. The emission factors used are CO₂-37 lb/ton; NO_x-0.025 lb/ton; SO₂- 0.0046 lb/ton; CO-0.40 lb/ton; PM-32 lb/ton or 16 kg/Mg. These emission factors are displayed in Table 1.

4.4.3 Emission Factors for Lime Manufacturing

The product obtained after calcinations of limestone at high temperature is called lime. The rock can be called limestone only if it has at least 50 percent calcium carbonate. Lime is also produced from chalk, coral, marble and sea shells. The basic processes in production of lime are quarrying of raw limestone, crushing limestone in kilns, calcining limestone, hydrating the lime and handling and storage operations. The rotary kiln is the most commonly used method in US for producing lime.

Apart from the gaseous pollutants, PM is the dominant pollutant. Carbon monoxide (CO), carbon dioxide (CO₂), sulfur dioxide (SO₂), and nitrogen oxides (NO_x) are also produced in kilns, but in lower amounts. CO₂ is emitted as a result of carbonate being reduced to CO₂ and carbon. In some plants the CO₂ generated is used in sugar refining. In sugar refining, hydrated lime is used with water for pH control and precipitate colloidal impurities. The lime added is then removed by reaction with CO₂. The emission factors used are based on the assumption that a coal-fired rotary kiln is used. This type of manufacturing is assumed because this is the only manufacturing process

for which emission factors are available for almost all pollutants considered. The emission factors used are: CO₂-1600; NO_x-1.6; SO₂-2.7; CO-0.74; all units are in kg/Mg. The emission factors are displayed in Table 1.

4.4.4 Emission Factors for Sand and Gravel Processing

The natural disintegration of rock or stone resulting in formation of sand and gravel results in alluvial soils. Sand and gravel are siliceous and calcareous products formed due to weathering of rocks and poorly consolidated materials.

Construction sand and gravel are mined in a wet or moist condition by dredging or by open pit excavation. After mining, transportation of materials to processing plants takes place using varied methods. Most sand and gravel used for domestic processes are processed before use. A combination of washers, screens and classifiers are used to segregate particles in different sizes. After transporting to processing plants, the wet sand is emptied into a hopper which has parallel bar screens to remove large cobbles and boulders. From the hoppers the material is transported to scalping screens to separate the various sizes of materials. Crushing follows and is generally carried out in two or three stages after which screening activity again takes place. Screening separates sand from gravel and after screening, the gravel is stored in storage bins. Industrial sand and gravel are mined from open pits of quartz-rich sand and sandstone and mining methods vary depend on cementation of rock. Mined materials are transported to a stockpile, crushed and size is further reduced to 50 micrometers by grinding. The ground material goes through a screening process. After initial screening, the sand and gravel are washed to remove impurities and the purified sand which has a moisture content of 15 to 25 percent is conveyed to drainage bins to reduce water content to 6 percent. The material is then dried in a rotary or fluidized bed and the material is cooled before being stored.

Emissions from production of sand and gravel consist primarily of particulate matter (PM). Apart from this, combustion products like CO₂, CO and NO_x are also formed.

Additionally, depending on the type of fuel used for drying, VOC and SO_x are also released.

Table 1 shows the various emission factors used as part of this study. General method adopted was adopting the highest value for quantifying the emissions and Table 2 is the emissions obtained from using Table 1.

Table 1: Emission Factors for Materials

Material	Emission Factor for CO₂ (kg/Mg)*	Emission Factor for NO_x (kg/Mg)*	Emission Factor for SO_x (kg/Mg)*	Emission Factor for CO (kg/Mg)*	Emission Factor for PM (kg/Mg)*
Lime	1600	1.6	2.7	0.74	-
Asphalt-Hot mix production	17	0.0275	0.0017	0.065	14
Sand and gravel processing	14	0.016	-	-	0.98
Cement manufacturing	1100	3.7	4.1	0.060	-

* Ref: US EPA (1995)

The emissions calculations for each material are shown in Appendix A. The emissions are calculated by multiplying the quantity of raw materials with the emission factors as shown in Table 1. The results of the manufacturing of materials phase area available in Table 2. The transportation of materials and machinery emissions are discussed in further sections of this chapter. Though there is difference shown in the results section for the same material, the emission factors used are the same. For e.g. lime slurry and lime used for treatment of sub base have the same emission factors.

Table 2: Emissions from Materials Manufacturing

Production of items	CO₂ (Mg)	NO_x (Mg)	SO₂ (Mg)	CO (Mg)	VOC (Mg)	PM (Mg)
Lime (slurry)	7447	7	13	3	NA	NA
Lime (treatment for sub base)	7285	7	1	3	NA	NA
Cutback asphalt	NA	NA	NA	NA	43	NA
Asphalt cement	NA	NA	NA	NA	0	NA
Emulsified asphalt	NA	NA	NA	NA	10	NA
Asphalt-	301	0	0	3	NA	0
Sand and gravel processing	1254	1	NA	NA	NA	88
Cement manufacturing	374	1	0	0	0	0
Sum	16661	18	14	10	52	88

NA= Not available

4.5 Emission Factors for Transportation of Materials by Trucks

The raw materials such as cement, lime and asphalt used for the construction of the road were brought in from in and around Texas. The method used for calculating emissions is the product of the quantity of materials, the distance transported, number of trips, and the emission factors. Emission factors for transportation of materials are provided by a computer model called MOBILE 6 (US EPA 2006).

MOBILE 6 is a software application that provides estimates of current and future emissions from motor vehicles. Emission factors are calculated for hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), and carbon dioxide (CO₂). The vehicles for which emissions are calculated are gas, diesel and natural gas fuelled cars, trucks and motorcycles for calendar year between 1952 and 2050. MOBILE 6 includes a variety of

default values which are used in the model as input values. Though most of the input values are optional and default values are provided, users are required to provide calendar year, maximum and minimum daily temperature and fuel volatility. Some of the input parameters include altitude, weekend/weekday, and fuel characteristic among others. Emission rates are obtained from actual emission tests conducted under standard conditions of temperature, fuel and driving cycle. Based on standard emission tests, the emission rates are assumed to deteriorate over time. These conditions are also provided by MOBILE 6.

MOBILE 6 is the general term used to describe the newer versions of the model, MOBILE 6.1 and MOBILE 6.2. MOBILE 6.1 adds the calculation of exhaust particulate matter, breaks and tire wear particulate, gaseous SO₂ and gaseous ammonia. Another feature added is to provide the output in a spreadsheet format. In addition to the above features, MOBILE 6.2 has the capacity to estimate CO₂ emissions though the emissions are not adjusted for speed, fuel content or vehicle maintenance program effects.

4.5.1 Running MOBILE 6

Starting MOBILE 6 prompts the user to enter a filename. A file generally consists of the pollutants which we want output for, the form in which the output is needed, for example, spreadsheet command provides the output in a spreadsheet format. Other input parameters include the calendar year for which pollutants are released, the minimum and maximum temperature, the sulfur content in fuel. A DOS path followed by a file name in the end is entered. For simplicity in execution, the input file can be placed in the same directory as the MOBILE 6 program. Also the directory can be made current, thus making it easier to input just the file name without the entire path. Another option is to leave a blank file name so that MOBILE 6 uses a default input file in the current directory. The program stops if no valid input file name is entered and no default files are located in the current directory. Once input file is entered, MOBILE 6 runs and messages of the model working appear on the screen. The more complex the runs are,

the longer the model takes to give an output. If there are no errors, the model shows the message “driver calls completed” and gives output.

4.5.2 Creating Input File

To create an input file, software applications such as Notepad or word processing software like WordPerfect need to be opened. The syntax to be followed for naming the files should be consistent with the DOS syntax: the name of file should be limited to eight characters plus an extension of three letters. The input commands required are entered and the file is saved as an ASCII DOS text file as MOBILE 6 does not recognize other file types. The commands used in input are provided in Appendix B of this thesis.

4.5.3 MOBILE 6 Outputs

The five kinds of output available in MOBILE 6 includes- database output report, descriptive output report, spreadsheet output, warning and error messages, use screen dialog. Database output is a descriptive form of output in a form suitable for use in a database management or spreadsheet. The descriptive output is in a format which is a summary and is suitable for printing. Spreadsheet output is similar to database output but is in a spreadsheet output.

4.5.4 Program Availability

MOBILE 6 is available with all related files and a User’s Guide from the EPA via the OTAQ website-<http://www.epa.gov/otaq/m6.htm>. The program runs only on a DOS based PC. All FORTRAN source codes and external data files are available in ASCII text format. MOBILE 6 does not run in any other platform other than DOS-based ones but it should be possible to run the program if FORTRAN 90 compiler application is available. System requirements include- IBM compatible 80386 or better or a Pentium, at least 8MB of RAM memory, and a math processor chip. The time taken to run each scenario depends on the type of processor the computer has. If a 400 MHz Pentium machine is used, each scenario takes about six seconds to run.

A model input file is shown in Appendix B. It calculates the emissions for all pollutants including CO₂. A variety of vehicles emissions can be estimated from using the MOBILE 6 software. For the purpose of this study, the materials were assumed to be transported by heavy duty trucks. The number of trips required was calculated (Calculations in Appendix A) based on the quantity required and the distance from site, and the emissions were calculated for two scenarios- hot temperature and cold temperature. The results are presented in Table 3 and Table 4.

This input file when run will give us emission factors for all possible vehicles for which MOBILE 6 calculates emission factors. Such an input file is used and emission factors for HC, NO_x, CO₂ and CO are obtained for heavy duty trucks.

The transportation of materials is assumed to be mostly carried out from Houston and Austin, the cities nearest to College Station in geographic location. These locations were chosen because the distance between these two cities and College Station is relatively small and the fuel costs can be saved by transporting from these places if materials are available here. The fuel assumed to be used by these trucks is diesel.

Table 3 : Emissions from Heavy Duty Trucks (Cold Temperature)

Heavy Duty Diesel Vehicle Emissions Calculations (Cold Temperature)				
Cement				
	Composite Emission Factors (g/mi)	Total Number of trips*	Distance per trip (miles)*	Emissions (Mg)
Composite VOC	0.622	10	240	0.001
Composite CO	3.642	10	240	0.009
Composite NO _x	14.529	10	240	0.035
Composite CO ₂	1438.8	10	240	3.453
Lime				
	Composite Emission Factors (g/mi)	Total Number of trips*	Distance per trip (miles)*	Emissions (Mg)
Composite VOC	0.622	339	214	0.045
Composite CO	3.642	339	214	0.264
Composite NO _x	14.529	339	214	1.054
Composite CO ₂	1438.8	339	214	104.379
RC Pipe				
	Composite Emission Factors (g/mi)	Total Number of trips*	Distance per trip (miles)*	Emissions (Mg)
Composite VOC	0.622	17	240	0.003
Composite CO	3.642	17	240	0.015
Composite NO _x	14.529	17	240	0.059
Composite CO ₂	1438.8	17	240	5.870

* Ref: Calculations in Appendix A

Table 4: Emissions from Heavy Duty Vehicles (Hot Temperature)

Heavy Duty Diesel Vehicle Emissions Calculations (Hot Temperature)				
Cement				
	Composite Emission Factors (g/mi)	Total Number of trips	Distance per trip (miles)	Emissions (Mg)
Composite VOC	0.558	10	240	0.001
Composite CO	3.114	10	240	0.007
Composite NO _x	11.944	10	240	0.029
Composite CO ₂	1430.4	10	240	3.433
Lime				
	Composite Emission Factors (g/mi)	Total Number of trips	Distance per trip (miles)	Emissions (Mg)
Composite VOC	0.558	339	214	0.040
Composite CO	3.114	339	214	0.226
Composite NO _x	11.944	339	214	0.866
Composite CO ₂	1430.4	339	214	103.770
RC Pipe				
	Composite Emission Factors (g/mi)	Total Number of trips	Distance per trip (miles)	Emissions (Mg)
Composite VOC	0.558	17	240	0.002
Composite CO	3.114	17	240	0.013
Composite NO _x	11.944	17	240	0.049
Composite CO ₂	1430.4	17	240	5.836

4.6 Emission Factors for Locomotives

Because high quality aggregates are not widely available in Texas, the aggregates for Highway 40 are brought in from Wyoming. The transportation of aggregate is assumed to be done by locomotives. MOBILE 6 does not give emission factors for locomotives. So emission factors were obtained from Environment Canada (Environment Protection Series 2004). The emission factors for each of the Criteria Air Contaminants (CAC) like NO_x, CO, HC, PM and SO_x produced from the locomotive operations are calculated in grams per liter (g/l) of fuel consumed.

Emission factors for freight, passenger trains and during switching operations is provided by this document. Tests were performed in the early 1990s by the Association of American Railroads (AAR), Southwest Research Institute (SwRI) and locomotive manufacturers and the emission factors were obtained from them. The emission factors were revised in 2001 and since then there has been further emissions testing of locomotives by SwRI for the US EPA and Transport Canada. The US EPA rules have three levels of limits for locomotive emissions corresponding to the date of locomotives manufacture and remanufacture which constitute Tier 0, Tier 1 and Tier 2. The Tier 3 limits will be introduced in 2012 and the limits are expected to be 90 percent below the other regulation levels. The Canadian fleet has been changed and now meets the requirements of Tier 0 and Tier 1 emission standards.

The emissions from locomotives are obtained as a product of the emission factors, the distance traveled and the amount of fuel consumed in liters (Calculations in Appendix A). The emissions obtained are given in Table 5. The distance from Wyoming to College Station is taken as the distance traveled by the locomotive. The distance was calculated by using driving directions from Google maps between Wyoming and College Station. Cheyenne, Wyoming was selected and the distance between College Station and Cheyenne by road and back was used.

Table 5: Emissions from Locomotives

Locomotive Diesel Fuel Emissions				
Aggregate (Locomotives)				
	Emission Factors (kg/L)	Distance traveled (miles)	Diesel fuel consumed (liters)	Emissions (Mg)
CO ₂	2.73	2,136	622,552	1,699.57
NO _x	0.05469	2,136	622,552	34.05
CO	0.01051	2,136	622,552	6.54
SO ₂	0.00254	2,136	622,552	1.58
HC	0.00273	2,136	622,552	1.70
PM	0.0013	2,136	622,552	0.81

4.7 Emission Factors for Machinery

The emissions from the machinery usage during construction are estimated using a computer model developed by the US EPA called NONROAD (US EPA 2005).

4.7.1 NONROAD Program

EPA classifies man made emissions into three categories- mobile, stationary and area sources. The mobile sources are further divided into on-road and nonroad emissions. Because nonroad sources contribute significantly towards air pollution, EPA has provided to help emissions estimates for nonroad sources meet the requirements of Clean Air Act of 1990.

Nonroad emissions occur from diverse equipment that falls under categories such as recreational vehicles, logging equipment, agricultural equipment and construction equipment. All categories of non road equipment except aircrafts, locomotives and boat

are included in the program. Fuel types which are included are diesel, gasoline, compressed natural gas (CNG), and liquefied petroleum gas (LPG).

The NONROAD model estimates emissions of hydrocarbons (HC), nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO₂), sulfur oxides (SO_x), and particulate matter (PM). The model estimates emissions at national, county and even sub county levels for inputs like population, load factor, available power and emission factor.

The three components of NONROAD program are the graphical user interface (GUI), the core model, and a reporting utility. The main purpose of a user interface is to make the NONROAD program more user friendly. With its pull-down menus, the user can quickly set up and execute a model scenario. Once the model scenarios are set up, the core model can be run and the reporting utility can be used to view and summarize the results.

The core model uses FORTRAN and contains all of the algorithms necessary for calculating emissions. The reporting utility creates standardized reports using output generated by the core model. The reporting utility uses Microsoft ACCESS and is a fully operational user friendly application. All the reports can be imported into a Microsoft ACCESS format. No prior knowledge of working with Microsoft ACCESS is required.

Reports for emissions by county, fuel type, equipment type, horsepower and a combination of these are given by the NONROAD program. The input required for generating the output is the product of equipment population for base year or the year for which emissions need to be calculated, average load factor or the fraction of the available power, available power, the power used to run the equipment given in horsepower, and activity in hours per year, emission factors from EPA . The core model generates an ASCII file which can be imported into the reporting utility by specifying

the file name. The reporting utility uses ACCESS to display the results. Excel or other spreadsheet programs can also be used for importing and displaying the results.

Using the NONROAD model, the emissions in grams per day were obtained for all the possible construction equipment used on and off the site. To obtain the emissions in an entire year, the productivity of the machinery used needs to be calculated. The equipments most commonly used were identified and their productivity calculated, the calculations of which are given in Appendix A. Some of the machinery which is used in the construction process is described in detail in the following sections.

4.8 Equipment Descriptions

4.8.1 Excavators

Many excavators available run on hydraulic power. The different types of excavators available are crawler or rubber-tire-carrier-mounted and a variety of operating attachments. Since there is such a large variety of excavators and operating attachments, there are many differences in the applications in which each type can be used. Also, there are economical benefits of using one over the other in the appropriate conditions. The key to operations of an excavator is hydraulic power as it provides a faster cycle time, ease in operation, good attachment control, high efficiency and greater accuracy and precision (Peurifoy et al 2002).

The classification of hydraulic excavators is based on the digging motion of the hydraulically controlled boom and stick onto which the bucket is attached. An excavator with a downward arc motion is called a hoe and it excavates by pulling the bucket towards the machine and curling inward. Another common motion is the upward motion known as front shovel. This machine operates by heaping the material away from

machine. The production of an excavator can be calculated by the following steps assuming it is a single unit.

- The heaped bucket volume also known as loose volume value is obtained from the manufacturer
- A bucket fill factor is applied which is dependent on type of machine and class of material
- A peak cycle time which is a function of machine type, and job conditions is estimated
- An efficiency factor is applied and the production rate is calculated.

4.8.2 Asphalt Pavers

The components of an asphalt paver include a tractor which is either track or rubber-tired and a screed. The tractor unit has a receiving hopper in front and a system of conveyors which move the mix through a tunnel at the back of the tractor unit. The mix is deposited on the road surface to be paved and to spread the mix evenly on the surface, augurs are used. The asphalt placement, depth, width are controlled by the screed and it imparts initial finish and compaction of material. The productivity calculations are provided in Appendix A of this thesis.

The material can be received directly into the hopper or the traditional method of dumping the material directly into the hopper from a truck. Push rollers are mounted on front frame of paver. (Peurifoy et al 2002)

4.8.3 Compaction Equipment

Because there is a strong relationship between pavement air voids and mechanical stability, durability and water permeability, asphalt pavements are designed based on the mix being compacted to a specific density. The norm for pavements is to have the air void content between 3% and 5%. The factors that affect compaction are temperature and characteristics of the mix, the operational features available in the compaction

equipment and the lift thickness. The two types of compaction equipment available are pneumatic tire and steel wheel vibratory rollers. The contact surface area available is a function of the roller width and the cylindrical wheel surface. As rolling progresses, the contact area available for compaction decreases. The compaction capabilities of the compacting devices can be adjusted to suit the construction activity. For a vibratory compactor, altering the frequency and amplitude alters the compaction effort thus giving additional compaction flexibility. (Peurifoy et al 2002)

Compaction is generally achieved in three steps- breakdown rolling, intermediate rolling, and finish rolling. The breakdown rolling generally attempts to achieve a required density within a time frame with the constraints of temperature and paver speed. But sometimes compaction is not achieved in single rolling, so an intermediate rolling is required to supplement the initial step of breakdown rolling. The last step, finish rolling is done to remove any marks made by the previous rolling attempts. The productivity calculations are given in Appendix A.

4.8.4 Bull Dozers

A dozer is equipment which has a tractor power unit and a blade attached to its front. There is no volumetric capacity for a dozer and the amount of material that the dozer moves is dependent on the material that will remain on the front when the blade pushes the material. They are generally used for drawbar work and so they have low center of gravity. Dozers are generally used for pushing materials or dozing, land clearing, ripping, assisting scrapers in loading and in general removing other pieces of construction equipment. The two major types of dozers are wheel dozers and crawler dozers. Both have their respective advantages in terrain suited for them. Based on the type of soil available on site, the dozer best for the site is used (Peurifoy et al 2002). Productivity calculations provided in Appendix A.

4.8.5 Scrapers

Scrapers are designed to load, haul and dump loose material. There are six steps for a production cycle of a scraper: loading, haul travel, dumping and spreading, turning, return, and turning and picking up another load. Scrapers can be used for a variety of materials and are economical when it comes to hauling over long haul conditions. These machines are capable of self-loading and hence the work at site is not interrupted if a machine stops working. They may not be the most suitable equipment for some construction jobs as excavators have better loading capabilities and trucks are more useful in hauling materials over long distances. But they are useful when the site is quite distant from the urban areas and also, the scraper deposits materials in uniform thickness, thus making compaction operations easier. The two main categories of scrapers are pusher-loaded and self loading. Each type has several sub-categories under them. The productivity calculations are available in Appendix A.

4.8.6 Loaders

This equipment is used to handle and transport bulk material in a construction site, to excavate, and to charge aggregate bins at asphalt and concrete plants. On the basis of running gear, it is classified into two types: crawler tractor mounted and the wheel-tractor mounted. Further grouping can be done based on the bucket type and the weight capacity of the bucket. The productivity calculations are given in Appendix A.

4.9 Results Tables

Based on the NONROAD program, the emissions were obtained for the construction equipment. These are shown in Table 6. The NONROAD program was run for construction and mining equipment for the base year, 2005. The output was obtained by using the GUI for input of values and the output is obtained in a spreadsheet format.

Table 6: Emissions from Non Road Equipment

Classification	EQUIP	CO exhaust	NO_x exhaust	CO₂ exhaust	SO₂ exhaust	PM exhaust
Construction and Mining Equipment	Bore/Drill Rigs	4.4E-02	3.9E-04	8.5E-02	1.8E-05	1.7E-05
	Cement & Mortar Mixers	1.5E-01	8.2E-04	2.6E-01	5.4E-05	3.9E-05
	Concrete/Industrial Saws	5.1E-01	2.6E-03	8.0E-01	1.6E-04	3.2E-03
	Cranes	6.0E-03	2.0E-04	2.2E-02	4.6E-06	1.9E-06
	Crushing/Proc. Equipment	2.2E-02	1.3E-04	3.6E-02	7.4E-06	1.7E-05
	Dumpers/Tenders	2.3E-02	1.3E-04	4.2E-02	8.6E-06	5.3E-06
	Other Construction Equipment	7.0E-03	3.1E-04	3.0E-02	6.3E-06	2.5E-06
	Pavers	4.9E-02	3.8E-04	8.5E-02	1.8E-05	9.9E-06
	Paving Equipment	1.8E-01	9.5E-04	3.0E-01	6.2E-05	1.0E-04
	Plate Compactors	9.2E-02	4.6E-04	1.6E-01	3.2E-05	7.7E-05
	Rollers	9.2E-02	6.7E-04	1.5E-01	3.1E-05	1.7E-05
	Rough Terrain Forklifts	8.0E-03	3.5E-04	3.5E-02	7.3E-06	2.9E-06
	Rubber Tire Loaders	1.9E-02	8.8E-04	8.7E-02	1.8E-05	7.0E-06
	Signal Boards/Light Plants	4.0E-03	1.9E-05	6.0E-03	1.3E-06	1.6E-06
	Skid Steer Loaders	5.2E-02	9.0E-04	1.3E-01	2.7E-05	1.2E-05
	Surfacing Equipment	8.1E-02	3.9E-04	1.2E-01	2.5E-05	1.8E-05
	Tampers/Rammers	5.4E-02	2.4E-04	1.0E-01	2.1E-05	1.2E-03
	Tractors/Loaders/Backh oes	1.2E-01	6.0E-04	1.8E-01	3.7E-05	2.1E-05
	Trenchers	1.5E-01	1.2E-03	2.6E-01	5.4E-05	3.6E-05
	Sum	1.7E+00	1.2E-02	2.9E+00	5.9E-04	4.8E-03

The final results depicting the combination of all the parts in a process based approach is presented in Table 7.

Table 7: Total Emissions from Process-Based Approach

Estimated Emissions in Mg						
Source	CO₂	NO_x	CO	VOC	SO₂	PM
Materials	16661	18	10	52	14	88
Heavy duty vehicles	227	2	1	<0.01	NA	NA
Locomotives	1700	34	7	NA	2	1
Machinery	3	<0.01	2	NA	<0.01	<0.01
Sum	18590	54	20	52	16	89

Based on the emissions obtained from the process-based approach, the materials phase contributes the maximum in terms of CO₂ emissions. There is a lot of uncertainty related to the emission factors used in the manufacturing of materials. To identify the input values most affecting the output, a sensitivity analysis is performed. The material phase has a high value of emissions due to the large quantity of lime used. The CO₂ emissions can be reduced considerably if alternative methods of soil stabilization are used. Another large emissions producer is the locomotives phase. The aggregates are brought in from long distances for construction work in Texas. The availability of good quality aggregates in and around Texas will eliminate the use of locomotives thus further reducing emissions produced. A comparison of the process-based results is done with the EIOLCA approach to gain confidence in the results obtained.

CHAPTER V

ECONOMIC INPUT-OUTPUT APPROACH

5.1 Introduction of EIO LCA Concept

A group of researchers from Carnegie Mellon's Green Design Initiative became interested in environmental life cycle assessment as a tool which could be useful in designing products, processes and policies. The goal was to create a sustainable economy and to find cost effective ways to reduce pollution. The Economic Input-Output Life Cycle Assessment (EIO LCA) method was developed to address issues which the previous process-based approach could not address. In particular, the process-based approach takes a long time, a lot of data is necessary, and it is difficult to assemble. The input- output economic models that underlie the EIO LCA approach were first developed by Wassily Leontief for the United States economy, and this work was the basis for the Nobel Prize in Economics in 1973. The EIO LCA concept was developed from this model to account for environmental impacts (Hendrickson et al 2006)

EIO LCA views the economy producing goods and services as aggregate and thus it uses two major simplifications. The first assumption is that there is a linear relationship between inputs and outputs. For example, the inputs increase by 10% if the outputs increase by 10%. The second assumption is that there are approximately 500 sectors which cover all the products services and sectors of the US economy. The average sector in the model accounts for approximately \$27 billion in output. Some sectors like electricity are much larger (\$213 billion) than others such as tree nut farming (\$2 billion). The Department of Commerce has created an input-output table based on these simplifications and an EIO LCA tool has been created by adding in the resources extracted and the discharges to the environment. Comparing with the process-based approach, the EIO LCA does not need a tight boundary and the entire economy is covered. However, the sectors are at an aggregate level and individual cases where the

input variables are different from generic cases, are not accounted for. Another advantage is the method is cheap and very quick and an LCA can be performed in a few hours whereas the process based approach takes a lot of time.

5.2 Environmental Impacts Addressed

Hendrickson et al. (2006) suggests a variety of environmental impacts that can be included in life cycle assessment studies. These include

- The impact on resources (renewable and non renewable) due to use.
- Changes in landscape and its loss.
- Air pollution
- Soil pollution
- Chemical and biological discharges into the surface water
- Noise
- Electromagnetic radiation
- Ionizing radiation

The International Organization for Standardization (ISO) defines impact factors for various impact categories as an initial step in the LCA. The example cited is the climate change which is made an impact category in an LCA. The factors included in the EIOLCA approach are-

- Conventional pollutants discharged into atmosphere and those having potential of causing global warming.
- Toxic wastes discharged into air, soil and water
- Energy inputs of fuels and electricity
- Non renewable resources such as ores, fertilizers and water.

5.3 Procedure for EIOLCA

The basic steps of an EIOLCA are as explained. The first step is to identify a purchase of a product or service. The purchase may be a manufactured item like a vehicle or the fuel used to run the vehicle. This purchase which has an economic value, and this value is the input for the EIOLCA model. The supply chain requirements associated with the purchase are identified in the model. The software also calculates the discharges to the environment for the entire supply chain. The process continues until all of the manufacture, use, and disposal stages are represented.

The advantage of this approach is that it is faster in the sense that an LCA can be conducted in a few hours. The EIOLCA is available free for anyone to use on the Internet. Also, the entire economy is included and there is no necessity of tight boundaries around the system for assessment. The only boundary as such is that only the US economy is considered for the life-cycle assessment. But this method when used provides the effect of a dollar purchase on the entire US economy thus giving us a supply-chain effect.

5.4 EIOLCA

The EIOLCA software (Carnegie Mellon University 2006) used in this study is available on the Internet at www.eiolca.net. The initial step is selecting the sector out of the 480 sectors. For this case study, the highway, street and bridge sector is used. Choices of data output appear which include economic activity, conventional air pollutants, greenhouse gases, energy, toxic releases and employment. Also, the level of increased activity, which means the economic activity which creates a supply chain effect in the economy, is asked as an input. The value of work (\$6,810, 725 scaled down to value in 1995 which is \$4,390, 254) is used as the input value, and, depending on the criteria specified, the output is displayed. The discount value used for scaling down the value of work is 5%. The output for the EIOLCA done is shown in Table 8. As expected, the power

generation, truck transportation, cements manufacturing and oil and gas extraction are the highest contributors to CO₂ emissions.

Table 8: Emissions from EIOLCA Approach

EIOLCA (original)

Estimated emissions in tons						
Source	CO₂	NO_x	SO_x	CO	VOC	PM
Materials	440	1	1	1	5	0.32
Heavy duty vehicles	286	1	0.06	20.48	1.52	0.04
Locomotives	24	1	0.04	0	0	0.02
Machinery	NA	NA	NA	NA	NA	NA
Sum	750	4	1	21	7	0.37

NA-Not Available

The EIOLCA method gives us much lower values than the process-based approach. The model gives the emissions which can be expected from any road under any geographic location under any weather and local conditions. It does not distinguish between different locations, soil types, and local weather conditions. Another EIOLCA approach which is yet to be publicly available is used to determine whether similar results are obtained.

5.5 EIOLCA-Hybrid Approach

The EIOLCA approach has been improved to allow for input values for each and every product or service in the supply chain (Carnegie Mellon University 2007). However, this approach is not yet publicly available, so the link to the online version of the method

cannot be given here. I was granted access to the tool by Carnegie Mellon University researchers.

This is a relatively new improvement and the procedure to be followed is the same. But extra input can be provided for each supply chain process or service. In this case study, the highest contributor to airborne emissions based on the process-based model is the lime. So in the supply chain, the amount spent for lime, asphalt and aggregate were added in the various line items for the model along with the total value of work. The results of this approach are as shown in Table 9.

Table 9: Emissions from EIO-LCA-hybrid Approach

EIO-LCA – hybrid

Estimated emissions in tons						
Source	CO₂	NO_x	SO_x	CO	VOC	PM
Materials	4935	1	1	7	6	0.33
Heavy duty vehicles	323	2	0.07	23.12	1.72	0.04
Locomotives	30	1	0.05	0	0	0.02
Machinery	NA	NA	NA	NA	NA	NA
Sum	5287	4	1	30	8	0.39

NA-Not Available

The hybrid approach has a considerable increase in the total emissions. But in comparison with the process-based approach, both the EIO-LCA models are underestimating the CO₂ emissions. The EIO-LCA models are based on economic activity. Even if the hybrid approach incorporates the amount spent on each of the

activity in a construction process, the unit price of the item in concern should be high enough for the EIOLCA and process-based models to have similar results.

CHAPTER VI

SENSITIVITY ANALYSIS

6.1 Introduction

Sensitivity analysis is a necessary tool for decision making. Sensitivity analysis helps in figuring out which variable is affecting the decision the most. The variables that are included in the decision making process are the ones that matter and the ones that are left out do not matter. Determining which of the variables are important in the decision making process uses sensitivity analysis (Clemen et al 2001)

Decision making many times involves questioning the problem being dealt with and whether the correct problem is being solved. Addressing a different problem or question can lead to different solutions. Type I and Type II errors are the most common ones in statistics. These errors involve incorrect conclusions formed for a problem. In the decision making process there is a third kind of error called Type III error. This involves asking the wrong questions thus arriving at incorrect solutions to a problem. To avoid Type III error, the only solution is to constantly question the problem.

6.2 Tornado Diagrams

A tornado diagram is helpful in comparing sensitivity analysis results for many input variables. The input variable is set between two boundaries of higher and lower values and the outputs are calculated with the variables set at these bounds. A tornado diagram helps us to visually understand which input variable affects the output. A tornado diagram looks like a series of horizontal bars of varying lengths. The length of the bar shows the extent to which input is sensitive to the output. A sensitivity analysis can be performed repeatedly with a different set of variables. After an initial tornado diagram is formed, an initial screening at base values of the inputs can be done. This means that

certain values are left out after the initial screening. But to increase precision, for the left out values in initial screening, a sensitivity analysis is performed again to determine the most important ones in the left out values.

6.3 Sensitivity Analysis Using TopRank

TopRank is a general sensitivity analysis program which can perform an analysis using spreadsheets. There are two options in TopRank, a fully automated version where instructions are followed or a user designed sensitivity analysis. In the automated model, all default settings are used and this method may not be suitable for every situation. The first step is varying the input. In an automated system, this command automatically varies the input between plus and minus 10%. For example, an input value of 75 will vary between plus and minus 10%, so that the values will be between 67.5 and 82.5. The default value for number of recalculations the TopRank conducts is 4. So if we have 10 input parameters, the program will recalculate the spreadsheet 40 times.

To start a sensitivity analysis, both Excel and TopRank are opened. A spreadsheet is opened or designed for doing a sensitivity analysis. The desired cell for which sensitivity analysis needs to be done is made the output variable by clicking on “Add Output” button. Once this is done, all the input variables related to the output are automatically varied based on Auto Vary functions. To perform a sensitivity analysis, the “Run What-If Analysis” button is clicked. This leads us to a window which is split into a Results section and a Detail by Input section. The Results window summarizes the analysis and the Detail by Input shows the input values used in the sensitivity analysis. The Results window has a few buttons at the bottom. The first button, Summary shows the summary of results. The second button, Detail shows the values which affect an increase over 20% by a blue upward pointing arrow and those that cause decreases below 20% by a downward pointing red arrow. The Actuals button replaces the percent values in the results page with the actual dollar values associated with the input. To return to the

default values, the button, Percent% is clicked. To obtain a visual description of the results, the button, “Graph” is clicked. It shows three options: tornado graph, sensitivity graph and spider graph. To obtain a tornado graph, that option is selected and a tornado diagram is produced.

In a custom version, the basic structure remains the same but instead of accepting default values we use a button called “Step Through Input Values” to change the input values. This provides us with an option to give the upper and lower bounds to values which we want to input. The next steps are the same: Running What-If analysis, Graph and a tornado diagram. The custom version has more necessity of input by the user but for a beginner the standard default version can yield results too.

6.4 Sensitivity Analysis for Case Study

6.4.1 Sensitivity Analysis for Manufacture of Materials

For this study, a sensitivity analysis was performed to identify which input values were impacting the output. The sensitivity analysis was performed on the process-based approach results and mainly on those results which were of significance to the overall CO₂ emissions. Thus a sensitivity analysis was performed on the materials and their transportation (trucks and locomotives).

For manufacture of materials, the input values are emission factors and quantity of materials. The emission factors were varied by choosing a different emission factor and obtaining a lower and upper bound where possible from the AP-42 emission factors (EPA 1995). Table 10 shows the upper and lower bounds of the emission factors used in the manufacture of materials. The quantity of material was given default settings. The results of the sensitivity analysis are as shown in Fig 3. The total emission from CO₂ from the manufacture of materials was set as the output for the manufacturing phase of

the inventory. This was done to identify the relative importance of one input over the other which might have been difficult if each material was dealt with individually. The tornado diagram obtained has varying lengths of bars for different materials used. The length of bar for emission factor of lime is the longest. The rest of the bars are much smaller in comparison. This shows that emission factor of lime affect the result and has the highest degree of uncertainty. So with lesser uncertainty, a greater deal of accuracy can be obtained.

Table 10: Upper and Lower Bounds of Emission Factors

Material	Emission Factors used(kg/Mg)	Emission Factor(kg/Mg)-Upper bound	Emission Factor(kg/Mg)-Lower bound
Lime	1600	1600	1575
Asphalt-Hot mix production	17	19	17
Sand and gravel processing	14	15.4	12.6
Cement manufacturing	1100	1100	1082

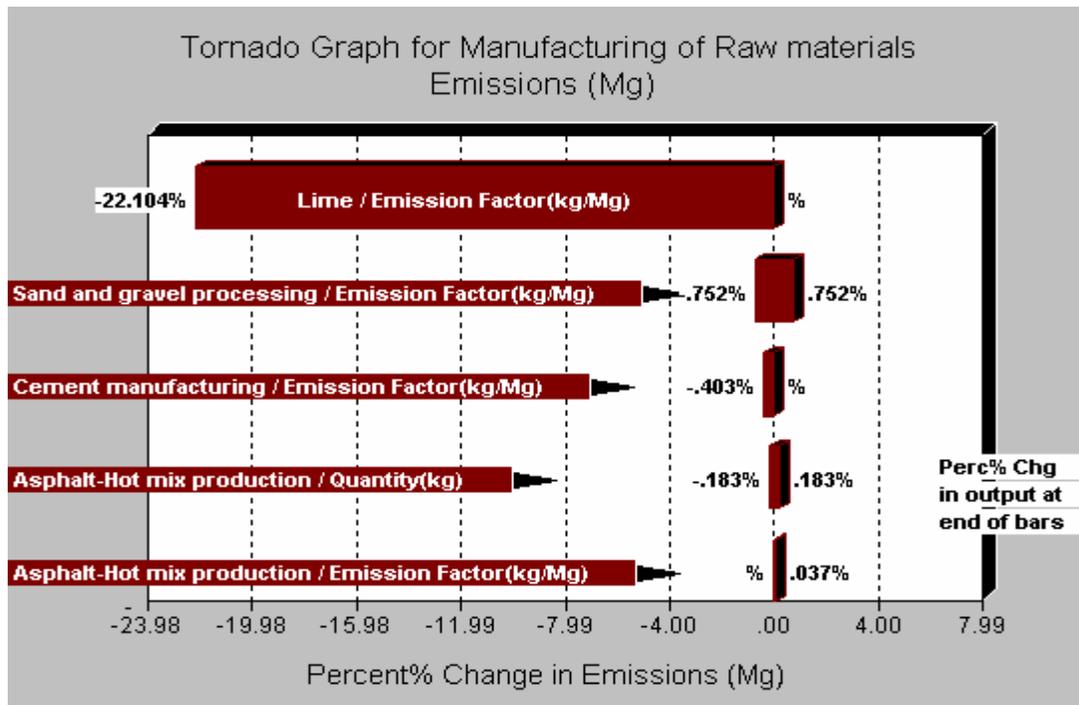


Figure 3: Tornado Diagram for Manufacture of Materials

6.4.2 Sensitivity Analysis for Transportation of Materials by Trucks

The input values in transportation of materials by truck are emission factors, the number of trips made and the distance traveled. Two scenarios are considered for sensitivity analysis- a hot temperature and a cold temperature. For each of these scenarios, input values are changed accordingly. For the transportation of materials by truck, the default values are assumed due to lack of proper data for the upper and lower limits.

In this case also, the input values are identified, the output is added and a What-If analysis is run for both scenarios separately. The output of the analysis is graphed on a tornado graph as shown in Fig 4 and Fig 5.

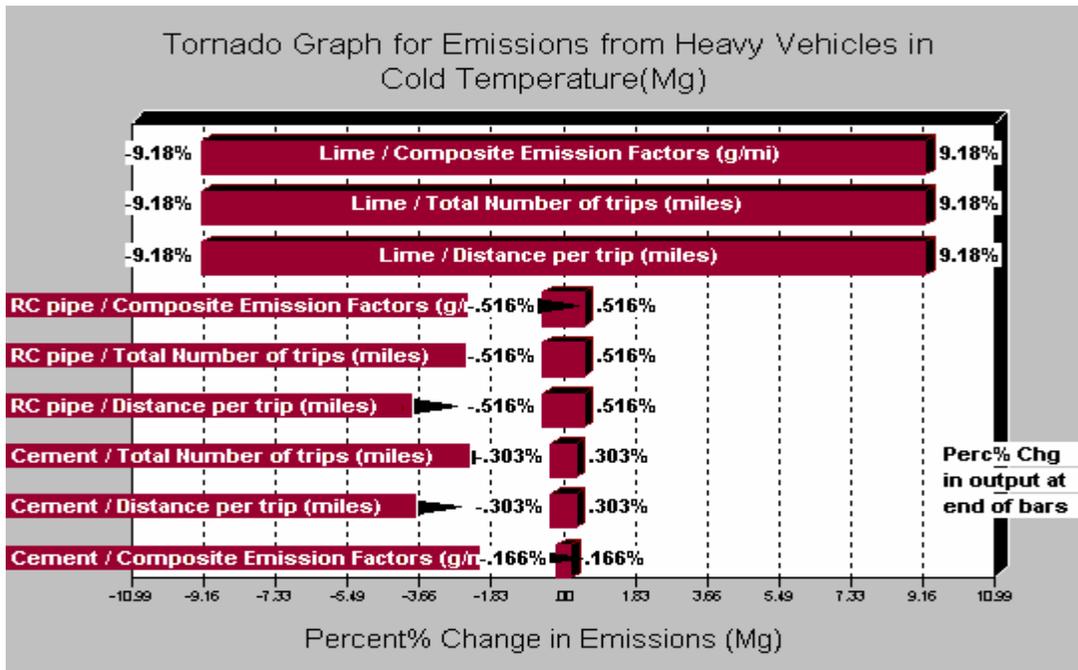


Figure 4: Tornado Diagram for Heavy Vehicles (Cold Temperature)

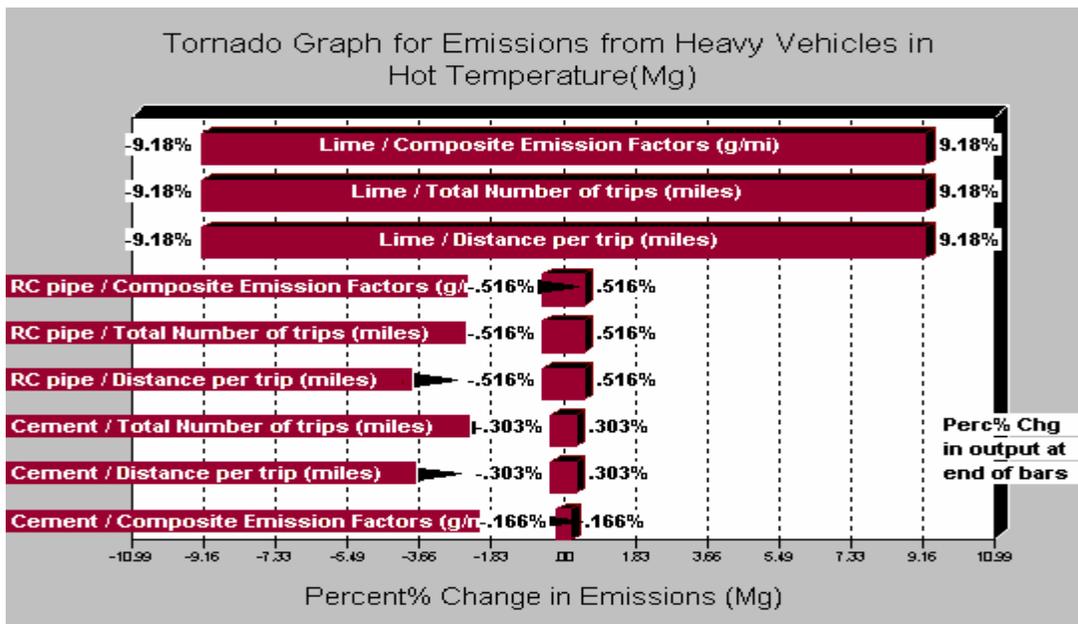


Figure 5: Tornado Diagram for Heavy Vehicles (Hot Temperature)

6.4.3 Sensitivity Analysis for Locomotives

The sensitivity analysis for locomotives is conducted by using the input values as the distance traveled, emission factors and the diesel fuel consumed. The emission factors and diesel consumed use the default values available in the program for upper and lower limits. But for the distance traveled, the upper and lower bounds are selected such that the shortest distance will be when materials are brought in from in and around College Station. Based on this the lower bound is set as the distance to Houston and the upper bound is the actual distance from where the aggregate is brought in. The rest of the steps are similar to the above categories like Running What-If analysis, and obtaining a tornado diagram. The tornado diagram for this section is Fig 6.

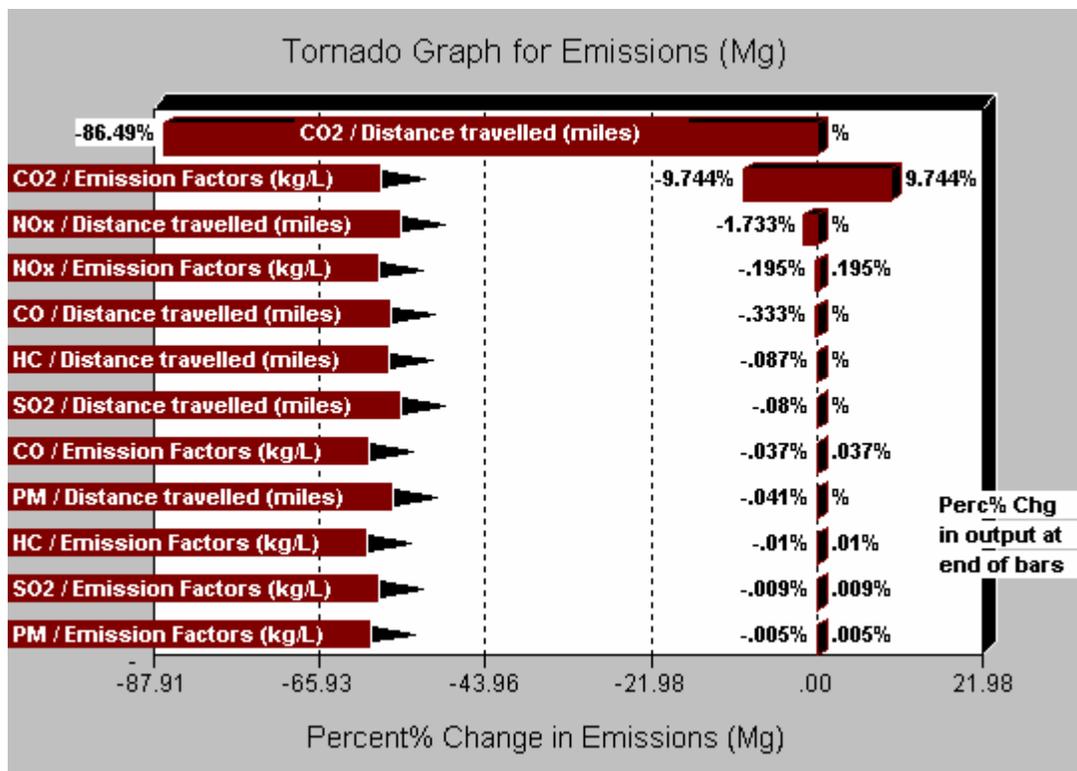


Figure 6: Tornado Diagram for Locomotives

The results from the tornado diagrams show that the distance traveled by the locomotives has a major role in the outputs. A solution of bringing the aggregate from in and around Texas will help reduce CO₂ emissions due to locomotives. There is a lot of uncertainty regarding the emission factors in all phases. A table showing the upper and lower bounds of the emission quantities is shown in Table 11.

Table 11: Upper and Lower Bounds of Emissions

Material	Emissions of CO ₂		
	Base qty	Lower bound %	Upper bound %
Lime	14732.00	-1.239	0.000
Asphalt	301.00	-0.019	0.173
Sand and gravel	1252.00	-0.675	0.672
Cement	374.00	-0.030	0.003
Locomotives	1699.57	-0.914	0.914
Heavy duty vehicles (cold temp)-cement	3.45	-0.002	0.002
Heavy duty vehicles (cold temp)-lime	104.38	-0.056	0.056
Heavy duty vehicles (cold temp)-RC pipe	5.87	-0.003	0.003
Heavy duty vehicles (hot temp)-cement	3.43	-0.002	0.002
Heavy duty vehicles (hot temp)-lime	103.77	-0.056	0.056
Heavy duty vehicles (hot temp)-RC pipe	5.84	-0.003	0.003

The table shows the upper and lower bounds of emissions from the materials, locomotives and the heavy vehicles by varying the emission factors. The top 11 contributors in CO₂ emissions were included to form the table. Since we are looking at the highest emissions, the materials phase was divided into its respective subdivisions of lime, sand and gravel, asphalt and cement. The rest of the phases remained the same. The emission factors for lime, asphalt and cement were varied on the basis of the absolute values available for their emission factors. All the other emission factors were varied on a basis of $\pm 10\%$. The table is a comparison of the various sensitivity analysis tornado graphs in a tabular form. The tornado graphs of the individual phases are obtained by using the upper and lower bounds for the emission factors and other components involved. To obtain a relative impact of the various items with respect to the total emissions, Table 10 is formed by varying the emission factors to the upper and lower bounds and dividing by the total emissions obtained from the process-based approach.

An analysis was conducted by using the lowest emission factors for the materials manufacturing phase as against the highest values used. The results showed that the emissions were reduced for the process-based approach but were again higher by a factor of approximately 20 from the EIOLCA method which again shows that the EIOLCA cannot be relied upon to give accurate results for individual case-studies. The actual estimate when the emission factors were set at lower bound for the manufacturing of materials phase is 15532 tons of CO₂ emissions. The total emission from construction of the road then becomes 17461 tons of CO₂. The EIOLCA method still predicts a lower value than the process-based approach even at the lowest available emission factors. The EIOLCA method does not take into account the large quantity of lime. The results obtained from the EIOLCA method do not give us an accurate picture of emissions from the construction of Highway 40. Since the EIOLCA works on the dollar value input, the only method in which the results between the two methods can be compared is when the unit price for a ton of lime is close to \$8.65. The results from the sensitivity analysis

show which input values affect the output the most. But based on the results of the comparison, it can be concluded that though there is a lot of uncertainty surrounding the process-based approach, the estimate of emissions provided are closer to the actual emissions released to the atmosphere than the EIOLCA approach.

CHAPTER VII

SUMMARY AND DISCUSSION

7.1 Summary

Three methods for conducting a life-cycle inventory assessment for highway construction have been discussed in this thesis, process based, EIOLCA, and EIOLCA-hybrid approaches. The difference in CO₂ emissions estimates between the process-based approach and the EIOLCA approach is an order of 1 magnitude. The CO₂ emissions estimate obtained from the process-based approach amount to a total of 18,590 tons including materials, transportation (locomotives and trucks) and machinery. The materials phase has the highest emissions and the number is 16661 tons of CO₂ produced. The EIOLCA approach, on the other hand, estimates CO₂ emissions of 1,160 tons. The EIOLCA-hybrid estimates CO₂ emissions as 5,287 tons. Since all the other pollutants are very small in numerical value as compared to the CO₂ emissions, they are not included for the discussion. But the relative percentage differences are provided in Table 12.

Table 12: Relative Percentage Differences between Methods

Pollutant	Process-based estimate	Relative % difference- EIOLCA	Relative % difference- EIOLCA-hybrid
CO ₂	18590	-96	-72
NO _x	54	-93	-92
CO	20	-94	-94
VOC	52	-59	-43
SO ₂	16	-58	-50
PM	89	-100	-100

The relative difference percentage for the CO₂ emissions from the EIOLCA-hybrid approach is much lesser than the original EIOLCA approach. But for the particulate matter (PM) emissions, the difference in estimates is almost a 100%. There is a lot of sand and gravel which is involved in the construction phase. The manufacturing of the materials releases almost 99% and the locomotives release less than 1% of the total PM in the process-based approach. The heavy vehicles and machinery do not contribute much (less than 0.01 tons) to the PM emissions. In the EIOLCA approach, the manufacturing of materials releases approximately 86% of the emissions and the locomotives and heavy vehicles together release 14% of the total PM.

There is a lot of uncertainty associated with the emission factors used. Because of this, a sensitivity analysis was performed to identify the input values most affecting the output. In the case of materials, it was found that the emission factor for lime followed by the emission factor for asphalt, sand and cement respectively were the input values which highly affect the output. Lime had the longest bar in terms of its emission factor. All the other materials had relatively smaller lengths implying that lime emission factor plays a major role in the results obtained from process-based approach.

For the transportation of materials by trucks, it was found that the emission factors, distance traveled and the number of trips required for lime had equal influence and that each of these input values affected the output in an equal manner. Lime had the longest bar for all three factors. The rest of the materials had relatively smaller lengths in comparison.

The distance traveled and the emission factors of CO₂ have the longest length in the tornado graph of locomotives. The other bars are of very short length but they still have an effect on the output. In all the phases, the materials phase has the maximum impact on the environment. The materials phase has increased the emissions to 18,592 tons of CO₂ where the emissions could have been less than 1000 tons otherwise.

7.2 Discussion

The case study road construction project is in Texas which has clay soil. This required the use of a large amount of lime to stabilize the soil. The CO₂ emissions from lime account for nearly 88% of the entire CO₂ emissions from material. Even in the process-based approach, the materials account for 90% of the total emissions followed by the locomotives which account for 9% of the total emissions. The truck and machinery emissions together make up for the last 1% of the total emissions. The process-based approach takes into account this high usage of lime for its calculations.

The EIOLCA gives us an aggregate view of the results obtained from highway construction. The results show that the method can be applied for any type of construction in any geographic location with any soil properties but the results will not account for local variability. Though the LCA takes very short time to perform, the results do not give us a good idea about the emissions from a road construction which has some other complications involved.

The EIOLCA-hybrid approach tries to rectify this problem in the EIOLCA by introducing input values for the various sectors involved in the supply chain. But the values still do not reflect the actual emissions which are emitted from the road. The EIOLCA approach tries to use a dollar value for estimating the emissions. So an increase or decrease in the dollar value has a parallel effect on the emissions. The dollar value for lime is very low. A ton of lime costs \$0.72. It was found that to obtain comparable results as with process-based approach, the unit price of lime should be increased to \$8.65. So increasing the dollar value to nearly ten times the actual value will produce results from this approach which are closer to the process-based results.

In general, the process-based approach will be a useful tool for projects which have a great deal of data and there is no constraint of time and manpower. The EIOLCA approach can be used to arrive at an estimate of emissions from a project and in some

cases, the EIOLCA results may be used as such without any changes. But a combination of both these approaches will provide the best estimate of environmental emissions from a project.

This research tried to estimate airborne emissions from a road which is actually constructed. The results obtained may be case-specific but they denote the actual values obtained from such a road construction. This research is the first of its kind to conduct an inventory assessment of a case study in the United States. By comparing the three methods available in literature, the results of this study prove that though the EIOLCA is a widely acclaimed method, the results obtained are not necessarily an accurate representation of emissions from individual highway construction projects. A better approach for the future would be to combine the process-based approach with the EIOLCA approach in such a manner that the initial material and energy balances are done in a process-based approach and the emissions obtained and the supply chain effects can be obtained from an EIOLCA. Though an inventory assessment of a road was conducted, the comparison of the three approaches provided us with information about the strong and weak points of both the process-based approach and an EIOLCA.

Future work can also look into sequestering or offsetting the huge amount of CO₂ released from highway construction projects. The ecological impact was out of the scope of this work. But an ecological impact assessment is necessary due to the high values of CO₂ which have been obtained after an inventory assessment.

REFERENCES

- Carnegie Mellon University Green Design Institute, "Economic Input-Output Life Cycle Assessment (EIO-LCA) Model" [Internet],
Available from: <http://www.eiolca.net/> (2006) (Accessed on December, 2006)
- Carnegie Mellon University Green Design Institute, "Economic Input-Output Life Cycle Assessment (EIO-LCA) Model" [Internet],
Available from: <http://www.eiolca.net/aurora-hybrid> (2007) (Accessed on April, 2007)
- Caterpillar Inc, (1996), *Caterpillar Performance Handbook*, 27th Edition, Caterpillar Tractor Co., Peoria, III
- Ciambrone D.F, (1997), *Environmental Life Cycle Analysis*, Lewis Publishers, Boca Raton
- Clemen R.T; Reilly T., (2001), *Making Hard Decisions with Decision Tools*, Duxbury Thomson Learning, Pacific Grove, CA
- Environmental Protection Series, (2004), *Locomotive Emissions Monitoring Program*, Environment Canada, Canada
- Hendrickson C.T.; Lave L.B.; Matthews H.S., (2006), *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach*, Resources for the Future, Washington DC
- Horvath A., (1997), "Estimation of Environmental Implications of Construction Materials and Designs Using Life Cycle Assessment Techniques", PhD Dissertation, Dept. Of Civil and Envir Engrg., Carnegie Mellon University, Pittsburgh
- Horvath A.; Hendrickson C., (1998), "Steel versus Steel-Reinforced Concrete Bridges: Environmental Assessment", *J. Infrastructure Systems*, 4(3), 111-117
- Horvath A., (2004), "Construction Materials and the Environment", *Annual Review of Environ. Resources*, 29, 181-204
- IPCC Global Warming Potential Page (2002),
"http://www.eia.doe.gov/oiaf/1605/gwp.html", Accessed on May 23rd, 2007

- Junnila S.; Horvath A., (2003), “ Life-Cycle Environmental Effects of an Office Building”, *J. Infrastructure Systems*, 9(4), 157-166
- Junnila S.; Horvath A.; Guggemos A.A., (2006), “Life Cycle Assessment of Office Buildings in Europe and the United States”, *J. Infrastructure Systems*, 12(1), 10-17
- Keoleian G.A; Kendall A.; Dettling J. E.; Smith V.M.; Chandler R.F.; Lepech M.D.; Li V.C., (2005), “Life Cycle Modeling of Concrete Bridge Design: Comparison of Engineered Cementitious Composite Link Slabs and Conventional Steel Expansion Joints”, *J. Infrastructure Systems*, 11(1), 51-60
- Little D., (1995), *Stabilization of Pavement Sub grades and Base Courses with Lime*, Kendall/ Hunt Publishing, Dubuque, Iowa
- Manual Series No. 4 (MS-4), (1962), *The Asphalt Handbook*, The Asphalt Institute, College Park, MD
- Mindness S.; Young J.F; (1981), *Concrete*, Prentice Hall Inc, Englewood Cliffs, NJ
- Park K.; Hwang Y.; Seo S.; Seo H., (2003), “Quantitative assessment of Environmental Impacts on Life Cycle of Highways”, *J. Construction Engineering and Management*, 129(1), 25-31
- Peurifoy R.L; Schexnayder C.J., (2002), *Construction, Planning, Equipment and Methods*, 6th Edition, Mc Graw-Hill Companies, Inc., Boston, MA
- Specifications, *Ohio Department of Transportation*,
[“http://www.dot.state.oh.us/Construction/OCA/Specs/2005CMS/300/306.htm”](http://www.dot.state.oh.us/Construction/OCA/Specs/2005CMS/300/306.htm)
 (Accessed in May 2006)
- Stripple H., (2001), *Life Cycle Assessment of a Road, a Pilot Study for Inventory Analysis*, 2nd Revised Edition, IVL Swedish Environmental Research Institute Ltd., Gothenburg, Sweden
- United States Environmental Protection Agency (US EPA), (1995), *AP 42*, Volume 1, Fifth Edition
- United States Environmental Protection Agency (US EPA), (2005), *NONROAD 2005*, Ann Arbor, Michigan

United States Environmental Protection Agency (US EPA), (2006), *MOBILE 6*, Ann Arbor, Michigan

United States Environmental Protection Agency (US EPA), (2007),

“<http://www.epa.gov/sustainability/>” (Accessed on April 2007)

Vignon B.W.; Tolle D.A.; Cornaby B.W.; Latham H.C.; Harrison C.L; Boguski T.L; Hunt R.G.; Sellers J.D. (1994); *Life-Cycle Assessment Inventory Guidelines and Principles*, USEPA Risk Reduction Laboratory, Lewis Publishers, Boca Raton

WCED, (1987), *Our Common Future*, Brundtland Report, World Commission on Environment and Development, Oxford University Press, Oxford

APPENDIX A

EMISSIONS CALCULATIONS

A.1 Manufacturing of Materials

A.1.1 Lime

Lime is assumed to be manufactured in a coal fired rotary kiln. The total quantity of lime as raw material in the BoQ is 4654.54 Mg. the total quantity multiplied by the emission factor gives the emissions to air. E.g. 4654.54 Mg of lime emits (4654.54 x 1600 kg) of CO₂.

For the item lime treated sub-base, dry density of lime is found out and assuming 6% of lime is used (Little 1995), the quantity of lime is found out by the formula- 6% x dry density of lime x (area given in BoQ x thickness of base). The quantity of lime thus found was 4553 Mg.

A.1.2 Asphalt

The hot mix quantity and the emulsified asphalt quantity are 18964 tons and 352510 liters respectively. These quantities multiplied with the emission factors give us the total emissions

For cutback asphalt, a major source of VOC emissions, a percentage of diluent used is assumed. Typically, for medium cure (MC) asphalt, 25 to 45% diluent is used. Solving two simultaneous equations as in (EPA 1995) which are as follows

$$0.8x + 1.1y = 188679$$

$$-0.55x + 0.45y = 0$$

where x is the volume of the diluent and y is the volume of asphalt cement

Solving for x and y we get the VOC emissions by assuming 70% evaporates.

A.1.3 Aggregates

For plane asphalt concrete, the percent by weight of asphalt is found out by the following formula from (Manual Series 1962)

$$P = 0.035a + 0.045b + 0.15c + F$$

Where P- % by weight of asphalt

a- % of aggregate retained on #8 sieve

b- % of aggregate passing #8 sieve and retained on #200 sieve

c- % of aggregate passing #200 sieve

F- Variable provided for adjustments for quantity of asphalt used

The weight of asphalt obtained is then converted to volume from which emissions are calculated

The aggregate volume (loose) given is multiplied by the density to give weight of aggregate. This value is then multiplied by the emission factors to give emissions.

The aggregate volume for plane asphalt is calculated by subtracting the volume of asphalt obtained previously. The emissions are then obtained as above

The product of thickness and area of flexible base gives a volume. The volume is then converted to weight by multiplying with aggregate density from which emissions are calculated.

Various sizes of box culverts are used for which wall thickness is assumed as 230 mm. design examples are taken from (Mindness 1981) which give the weight per volume of cement and aggregates. The emissions are the calculated as above for both cement and aggregate for each size of culvert

The weight per cubic meter for a cement treated base is taken from an example from (Specifications 2006). Cement and aggregate emissions are then calculated.

A thickness and depth is assumed for concrete curb and gutter. Assuming a proportion of 1:2¼: 3 quantity of raw materials required is calculated. The emissions are then calculated as above.

A.2 Emissions from Transportation of Materials

A.2.1 Truck Emissions

The emissions from the transportation phase are calculated based on the premise that the materials are transported by trucks and locomotives. The assumptions made are-

The type of trucks used to transport materials

The fuel used in trucks is gasoline

Methodology for calculating transportation emissions

The procedure for calculating the emissions is no. of trips required to transport materials with the number of miles required to transport the materials with the emission factors.

No. of trips = Quantity of material / capacity of truck

For example, for lime, the quantity is (4654.54 Mg+4553 Mg)

Capacity of truck is 27215 kg or 27.215 Mg

No. of trips = $9207.54/27.215 = 339$ trips

A.2.2 Methodology for Calculating Locomotive Emissions

The aggregate used in the project is brought from the state of Wyoming. It is assumed to be brought to Texas in locomotives. The emission factors are obtained from Canada (Environmental Protection Series 2004). The methodology for calculating emissions is as shown-

Total aggregate quantity – 87651 tons

Fuel usage = $3.3252\text{L}/1000 \text{ tons-km} \times \text{Distance (km)} \times \text{Qty of material (tons)}$
 $= 3.3252/1000 \times 2136 \times 87651$

Fuel usage = 622552L

Emissions in Mg = Emission factor (kg/L) x Fuel Usage (L)/1000

A.3 Emissions from Machinery Used

A construction site involves the use of a lot of machinery. In this research we have made a few assumptions about the usage of machinery. The assumptions are-

The type of machinery used

The time period of usage

The fuel used

Methodology for calculating machine emissions

The production rate of most machinery is calculated using the Caterpillar handbook and from a construction management textbook (Caterpillar 1996; Peurifoy et al. 2002). A sample calculation showing the production rate is shown below.

A.3.1 Production of Asphalt Paver-

Maximum Capacity = 2890 tons per hour (Caterpillar 1996)

Assuming a 8 hour work day

Asphalt paver capacity=23120 tons/day

A.3.2 Production of Bull Dozer-

Assuming a model of D11R

Blade capacities 34.4m³ and assuming a dozing distance of 30m

Estimated dozing production = 2100Lm³/hr (Caterpillar 1996)

Production = Maximum production x Correction factor

$$= 2100 \times 0.75 \times 0.8 \times 0.83 \times 1.20$$

Bull dozer production = 1255 Lm³/hr

Where Correction factors assumed are-

Operator – average = 0.75

Material – hard to drift, non-cohesive or very sticky material= 0.8

Job efficiency (50 min/hr) = 0.83

Slot dozing = 1.20

A.3.3 Production of Scraper-

Loading time assumed = 0.8 minutes (most economical)

Production per hour = 113 m³ i.e. Production per day is 904 m³/day (Caterpillar 1996)

A.3.4 Production of Track Loaders-

Assuming Model 973 is being used-

Rated bucket capacity and load factor are 2.8 m^3 and 1.0 respectively

Production = $2.8 \times 1.0 = 2.8 \text{ m}^3$ (loose)

Cycle time = Load time + maneuver time + travel time + dump time

$$= 0.03 + 0.2 + 0.2 + 0.1 = 0.53 \text{ minutes}$$

Loads per hour = 60 min/hr

$$0.53 \text{ min/ cycle}$$

$$= 113 \text{ cycles / hr @ 100\% efficiency}$$

Load per cycle = $2.8 \times 1.15 = 3.22 \times 0.81 = 2.61$ (bulk) m^3

Assuming 8 hour workday,

Production of track loader = 2360 m^3 / day

A.3.5 Production of Excavators-

Model 375L Excavator is assumed to be used at the work site

$$\text{Production} = \frac{3600 \times Q \times F \times (AS : D)}{t} \times \frac{E}{60 \text{ min hr}} \times \frac{1}{\text{volume correction}}$$

Where,

Q- Bucket capacity range = 1.5 m^3

F- Bucket fill factor = 100% (assuming bank clay, earth)

Estimated bucket payload = heaped bucket capacity x Bucket fill factor

$$= 1.5 \times 1.00 = 1.50 \text{ m}^3$$

Actual hourly production = 60 min hr production x Job efficiency factor

$$= 270 \times 1.00$$

Assuming 8 hours workday

A 375L excavator actual production per day = $270 \times 8 = 2160 \text{ m}^3$

A.3.6 Reclaimer Mixers-

Model RR-250B is assumed to be used at the work site

Production in yd³ per minute

$$\begin{aligned} \text{Yd}^3/\text{min} &= (\text{FPM of travel speed}/1.125) \times (\text{Cutting or mixing depth in inches}/36) \\ &= (98.044/1.125) \times (12/36) \end{aligned}$$

$$\text{Yd}^3/\text{min} = 29.05$$

Production in tons per minute

$$\begin{aligned} &= \text{Yd}^3/\text{min} \times (\text{Wt. of material per yd in lbs}/(2000 \text{ lb}/\text{ton})) = \text{tons}/\text{min} \\ &= 29.05 \times (2500/2000) = 366 \text{ tons}/\text{min} \end{aligned}$$

$$\text{Production} = 36 \text{ tons}/\text{min}$$

Assuming 8 hours workday

$$\text{Production of Reclaimer mixers per day} = 17280 \text{ tons}/\text{day}$$

A.3.7 Dual Drum Vibratory Asphalt Compactors-

Mat – 10 feet Mat thickness= 50mm= 2 inches

$10 \times 2 \times 110 / (9 \times 2000) = 0.122$ tons per ft of paving length where 110 is the density of asphalt in lb/ sy-in

Assuming 300 tons/hr asphalt plant capacity- $300/60 = 5$ tons/min

Average paving speed = $5/0.122 = 41$ ft/min = 0.47 mph

Rolling width = $(10 \times 12) + 2 \times 6$ (overlap) = 132 inches

Effective roller width = $47.2 - 6$ (overlap) = 41.2 inches

No. of laps = First lap – 47.2 inches. Remaining – 84.8 inches

Additional laps required= $84.8/47.2 = 1.79$ approximated to 2.

Total no. of laps = 3

Total no. of roller passes = 3 laps x 3 passes = 9 passes (Asphalt handbook 1962)

Production rate-

$$W \times S \times L \times 16.3 \times 0.83 / P = \text{yd}^3/\text{hr}$$

$$= 41.2 \times 0.47 \times 2 \times 16.3 \times 0.83 / 9 = 58.2 \text{ yd}^3/\text{hr}$$

$$2.38 \text{ lb}/\text{l} = 1820 \text{ lb}/\text{yd}$$

Production in tons per hour = $\text{yd}^3/\text{hr} \times \text{Wt. of material per yd in lbs} / (2000 \text{ lb}/\text{ton}) =$
tons/hr

$$= 58.2 \times 1820/2000 = 53 \text{ tons/hr}$$

Assuming 8 hour workday,

$$\text{Production of asphalt compactor} = 424 \text{ tons/day}$$

All the emissions from NONROAD are given in tons/day for a typical weekday in the base year which is 2005 in this case. The productivity of the equipment helps relate the emissions released from the equipment to the quantity of material being processed. For example, the asphalt compactor has a productivity of 424 tons/day. If the total quantity of asphalt available is 18964 tons, the total number of days to compact the material will be 45 days. Thus the emissions obtained from NONROAD are multiplied with the number of days the machine is used.

APPENDIX B**MOBILE6 INPUT FILE**

PARTICULATEs :
:

AIR TOXICS :
:

POLLUTANTS : HC CO NOX CO2

SPREADSHEET :
:

RUN DATA

>Example Run - Tests All M6.2 Pollutant Types

*

EXPRESS HC AS VOC :

EXPAND EVAP :
:

SCENARIO REC : Example Input File

CALENDAR YEAR : 2005

*

SULFUR CONTENT : 30.0

MIN/MAX TEMP : 40.0 96.0

FUEL RVP : 7.0

PARTICLE SIZE : 10.0

PARTICULATE EF : PMGZML.CSV PMGDR1.CSV PMGDR2.CSV

PMDZML.CSV PMDDR1.CSV PMDDR2.CSV

DIESEL SULFUR : 500.0

GAS AROMATIC% : 25.0

GAS OLEFIN% : 15.0
GAS BENZENE% : 1.5
E200 : 50.0
E300 : 85.0
OXYGENATE : MTBE 15.1 0.50
: ETBE 17.6 0.05
: ETOH 10.0 0.45
: TAME 6.0 0.00
ADDITIONAL HAPS : HAP_BASE.CSV

END OF RUN :

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