A Dynamic Life Cycle Assessment Tool for Comparing Bridge Deck Designs

By

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Abstract

A life cycle assessment (LCA) model was developed to compare the sustainability of alternative concrete bridge deck designs: one a conventional steel reinforced concrete (SRC) deck with mechanical steel expansion joints, and the other an SRC deck with engineered cementitious composite (ECC) link slabs.

The model was developed in Microsoft Excel based Visual Basic macros and includes five modules: materials, construction, traffic, distribution, and end-of-life. With over 100 flexible parameters programmed in the LCA computer model and the integration of three other computer programs, US EPA's MOBILE6.2 and NONROAD emissions models, and the KyUCP traffic model, users are able to explore the impacts of changes in material formulation, bridge deck design, and traffic flow.

The two design alternatives were evaluated over a 60-year time horizon: the ECC link slab system was modeled with a 60-year service life, while the conventional joint system required two bridge decks each lasting 30-years. Over this time period the ECC link slab system showed significant benefits in environmental performance relative to the conventional joint system, despite that ECC material is more energy intensive than conventional concrete. The ECC link slab system consumed 40% less total primary energy, produced 39% less carbon dioxide, and consumed an average of 38% less of key natural resources such as coal, limestone, and water. The most influential parameter in the model proved to be construction related traffic. For a 0% traffic growth scenario, construction related traffic energy comprised 80% of total primary energy consumed by the conventional system and 85% of total primary energy consumed by the ECC system. Construction related traffic also dominated results for the majority of air emissions including; hydrocarbons, carbon monoxide, methane, and greenhouse gas emissions.

This model provides a holistic set of environmental sustainability indicators that can enhance infrastructure design and investment decisions.

Acknowledgments

This research was funded through an NSF MUSES Biocomplexity Program Grant (CMS-0223971 and CMS-0329416). MUSES (Materials Use: Science, Engineering, and Society) supports projects that study the reduction of adverse human impact on the total interactive system of resource use, the design and synthesis of new materials with environmentally benign impacts on biocomplex systems, as well as the maximization of efficient use of materials throughout their life cycles.

This thesis would not have been possible without the guidance and support of Greg Keoleian and Jonathan Bulkley, and the contributions of others on the MUSES team, especially Richard Chandler, Jon Dettling, Vanessa Smith, and Michael Lepech.

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1 Introduction

1.1 Cement and its Significance

Our modern landscape cannot be characterized, described, or even imagined without concrete materials. Concrete's unique chemical properties that convert a pourable liquid into a rigid and durable solid have defined the architecture and infrastructure of our world. While cement is a material vital to human infrastructure and economy, its production contributes a significant amount of carbon dioxide (CO_2), a greenhouse gas, to the atmosphere; approximately 5% of total anthropogenic emissions (WBCSD 2002), and is one of the top two industry producers of CO_2 (van Oss and Padovani 2003). CO_2 is produced both during the combustion of fuels for kiln heat, and by the process of limestone calcination. Other important pollutants are produced during the production process as well such as nitrogen oxides and sulfur dioxide emitted from the cement kiln as a result of fuel combustion and heating of the material, and particulate matter emitted from the cement kiln and during the cement milling process (USEPA 1999, CIF 2000). Environmental impacts associated with these pollutants pose risks to human health and environmental and economic sustainability.

A holistic approach to evaluating and improving cement's impact on the global environment is needed to identify all the possible areas for improvement. Investment in infrastructure is costly from both economic and material standpoints. Devising a technique to predict long-term impacts of infrastructure design and material selection could provide a strategic approach for reducing environmental impacts over time. In this thesis a life cycle assessment (LCA) model is developed and applied to compare the environmental impacts for a bridge containing conventional steel-reinforced concrete joints, and an alternative design using link slabs constructed with a novel material – Engineered Cementitious Composites (ECC).

1.2 LCA – A Holistic Approach

Life cycle assessment (LCA) is an analytical framework (ISO 1997) for measuring environmental and social impacts of a product system or technology. LCA is often described as a "cradle to grave" examination of a product or process, highlighting environmental impacts and hidden costs that are often not reflected in conventional assessments, which may focus on narrower boundaries and short-term issues. Cement production, for example, requires a significant amount of energy to supply the high kiln temperatures required to generate the chemical reactions that convert limestone into clinker, the precursor to cement. This chemical reaction, or calcination, requires driving CO_2 out of the rock and into the atmosphere. Thus, the CO_2 emitted during cement production comes both from fuel combustion to run the kiln, as well as from the calcination process that occurs in the kiln. However, the production process alone does not account for the application, or use phase, of the cement product. Concrete materials provide a valuable service in their applications in infrastructure. While production impacts are important to recognize, so is the performance of the resultant material in the field. Durability may prove to be more important from a life cycle perspective than the impact of production, so a tradeoff between production impacts and performance during application may have to be made. This thesis examines the application of cement as applied in a concrete bridge deck. Cement, the binding agent in concrete, impacts the bridge deck system based on its performance. For example, when the concrete bridge deck cracks and repairs have to be made, traffic congestion results from the repair process as traffic patterns are altered and road capacity is reduced. The additional fuel used by these cars while they are delayed results in increased levels of CO_2 emissions. This fact highlights the need for a cradle-to-grave understanding of products and materials. Without it, the true impacts of using a material may not be understood.

Despite the drawback of its production impacts, cement remains fundamental to our modern infrastructure system and new, advanced cementitious materials are being developed that promise longer life, improved mechanical properties, and perhaps reduced life cycle emissions. Strategic application of these materials in new or existing structures is hoped to extend the life of infrastructure and reduce repair and reconstruction burdens. By building an LCA model for infrastructure applications that is able to compare conventional cement materials and ECC over the entire life cycle of the infrastructure application, an understanding of the potential benefits of these advanced ECC materials will be gained.

The LCA methodology is applied to two alternative bridge deck designs and evaluates the suitability of one design over another based on varying conditions specified in the model. The model is designed to be flexible by allowing changes in most model components, including bridge deck design, material selection, and traffic conditions.

1.3 Research Objectives

This project results from an interdisciplinary collaboration of researchers at the University of Michigan. Researchers with expertise in Civil Engineering, Industrial Ecology, Economics, and Economic Geology came together to explore the impacts and potential future improvements of cement materials in modern infrastructure.

The research for this project was funded through the National Science Foundation (NSF) with a Materials Use: Science, Engineering, and Society (MUSES) grant. The objective of the MUSES program is to reduce “adverse human impact on the total, interactive system of resource use, as well as maximizing the efficient use of individual materials throughout their life cycles.” (NSF 2004) In order to reach the goals of MUSES, an interdisciplinary group of researchers came together with a plan to integrate macro-scale modeling, in this case an LCA model, and microstructure tailoring of novel materials, ECC, in order to maximize the environmental benefits of material design over the life cycle of its application. This thesis has two primary objectives:

1) The development of the LCA model
2) The application of the model to a bridge deck system.

By reaching these objectives, the model provides macro-scale modeling capability to the research team.

1.4 Organization of this Report

This thesis is divided into seven sections. In this section a description of why cement and its impacts are an important topic of study, the origin of the study, and the need for a life cycle assessment approach are provided.

Section 2 provides a discussion of key background topics including, the system definition, an in-depth description of LCA, the goals of LCA model development, and previous research relevant to this study.

Section 3 focuses on LCA model development and highlights two key features of model development; defining the functional unit and the bridge infrastructure life cycle timeline used in the model.

Computer model development is discussed in Section 4. Computer model architecture and its relationship to each major phase of the LCA model are described. The logic sequence for each computer program module is outlined.

Section 5 describes the datasets used in the model and provides a summary of model limitations and assumptions.

The final results of the model are provided in Section 6. Life cycle impacts including raw material use, energy consumption, solid waste, air emissions, water discharges, and green house gas emissions are presented for the ECC and conventional systems.

Section 6 puts forward conclusions and recommendations for future research.

2 Background and Previous Work

2.1 Background

An estimated one-third of U.S. roadways are in poor or mediocre condition (ASCE 2001), burdening the public with construction related impacts such as congestion (TRIP 2002) and vehicle damage (ASCE 2001; TRIP 2002). Poor roadway conditions have lead to continued material and economic investment in highways and roads of approximately 260 million metric tons of concrete annually in the U.S. (Kelly 1998). This figure illustrates the need to approach road building and repair from a new perspective – long term and preventive, rather than short term and corrective. The life cycle assessment (LCA) methodology provides the means for this kind of evaluation.

The LCA framework is designed to evaluate a product or process throughout its life cycle, including raw material acquisition, production, use, final disposal or recycling, and the transportation needed between these phases (ISO 1997). Often, LCA elucidates unseen environmental and social burdens incurred over a product's lifetime.

2.2 System Definition

This study focuses on the development of a comparative LCA model. This means that multiple bridge designs can be assessed and evaluated. Two bridge designs are assessed in this thesis. They are a conventional steel reinforced concrete (SRC) deck with mechanical steel expansion joints, and an SRC deck with ECC link slabs. The design using a conventional SRC deck and steel expansion joints is shown on the left in Figure 1, and on the right the SRC deck with ECC link slabs is depicted. Throughout this paper the SRC deck with mechanical steel expansion joints is referred to as the conventional system, and the ECC link slab design is referred to as the ECC system.

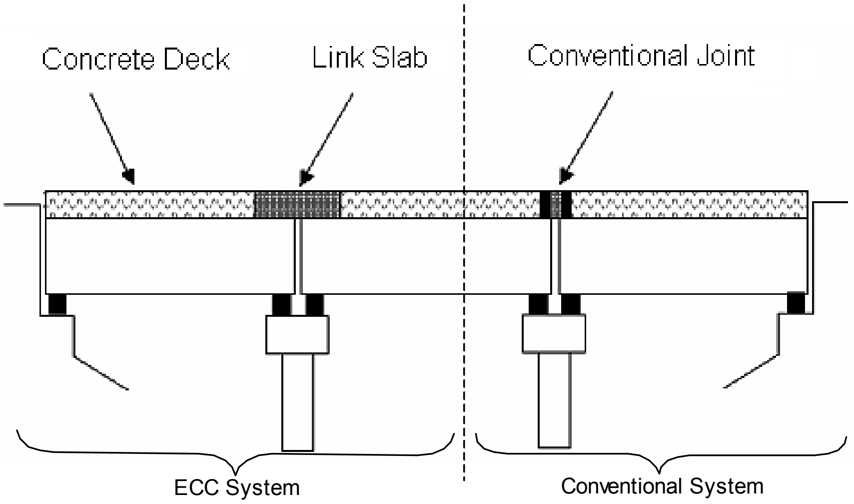


Figure 1. Bridge Deck with ECC Link Slab and Conventional Mechanical Steel Expansion Joint

The system boundary includes the impacts of the bridge design on its users. The impact on bridge users is manifested in construction related traffic, which increases fuel use and emissions, and also has broader economic impacts such as time lost to motorists or shipment delays to business. The time horizon in this model is always bounded at 60-years. This is an important assumption and will be discussed more fully in Section 3.

2.3 LCA Framework Described

The LCA framework can be described by four main phases: raw material acquisition, product manufacturing, product usage or consumption, and material waste. Within each of these phases solid waste, air emissions, and waterborne pollutants are produced and energy is consumed. Between each of these phases transportation of materials and waste is often necessary as well. Figure 2 shows a typical LCA flow chart.

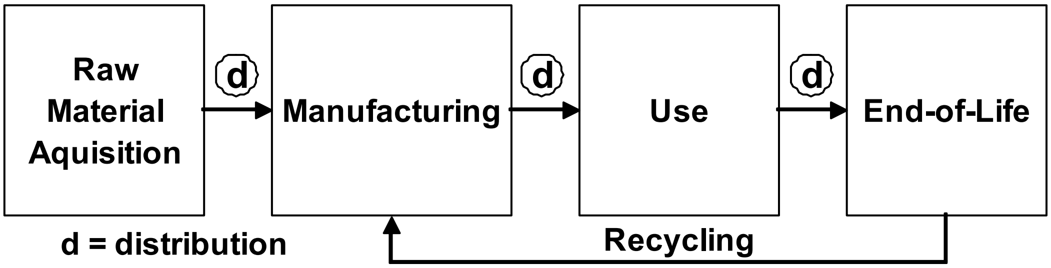


Figure 2. Generic Life Cycle Framework Diagram

If we examine the plastic fiber used in ECC through its life cycle using the diagram above, the raw material acquisition phase includes the drilling and refining of petroleum to create the precursors to plastic. These products must be transported to the manufacturing facility where they will be turned into plastic fibers. Manufacturing requires energy and material inputs, such as electricity for the manufacturing plant and process water used in manufacturing. The fibers must then be packaged and be distributed to their final customer. In this case the final customer is the person mixing and applying ECC. During its use-phase the ECC remains bound in the ECC matrix and does not create any outputs or use any inputs. Finally, in the end-of-life phase the ECC link slab is removed and trucked to a landfill. At this time there is no way to recycle the plastic fibers entrained in the ECC, so the recycle loop shown above is not used. In between phases where transport of the material occurs the fuel use, emissions from combustion, and upstream burdens for fuel production need to be accounted for. This is the life cycle of the plastic fiber, which is a single component in the life cycle of the bridge deck system.

Figure 3 shows the life cycle flow diagram for a bridge deck system. Note that the bridge deck system's use phase cycles between normal traffic flow and periods of construction where reinvestment in the deck takes place. The periodic reentry of the bridge into the construction phase adds complexity to the LCA model. The uncertainty in terms of when re-construction and repairs may be needed highlights the need for sensitivity analysis in the temporal dimension.

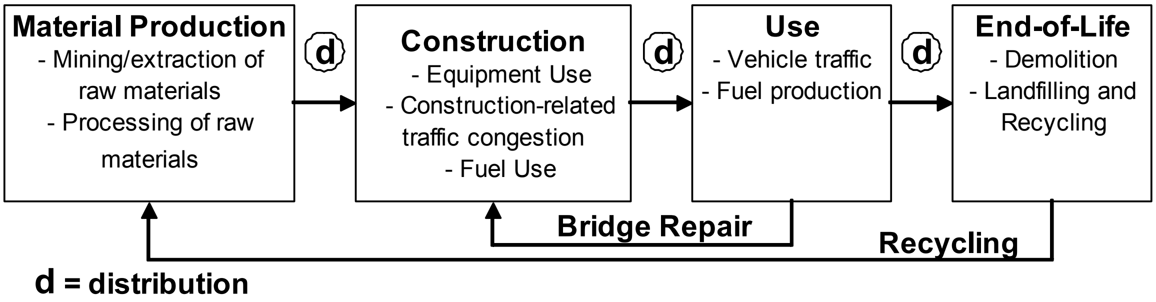


Figure 3. Bridge Deck System Life Cycle Framework Diagram

In modeling the framework described in Figure 3, each material and energy input to the system requires a dataset that reflects the burdens and inputs associated with its own life cycle, as outlined in Figure 2. For example, when modeling a bridge construction event not only must the hours of operation and fuel economy of each piece of equipment be defined to estimate fuel consumption, but also the life cycle data for the diesel consumed by the machinery including upstream burdens (burdens associated with petroleum extraction, refining, and transport) and the impacts of combustion such as the release of air pollutants. Figure 4 is an expanded diagram of the bridge deck system life cycle assessment. The figure includes the upstream burdens for fuels as well as the emissions created during combustion. The model also accounts for material production burdens such as raw material acquisition, and air and water emissions.

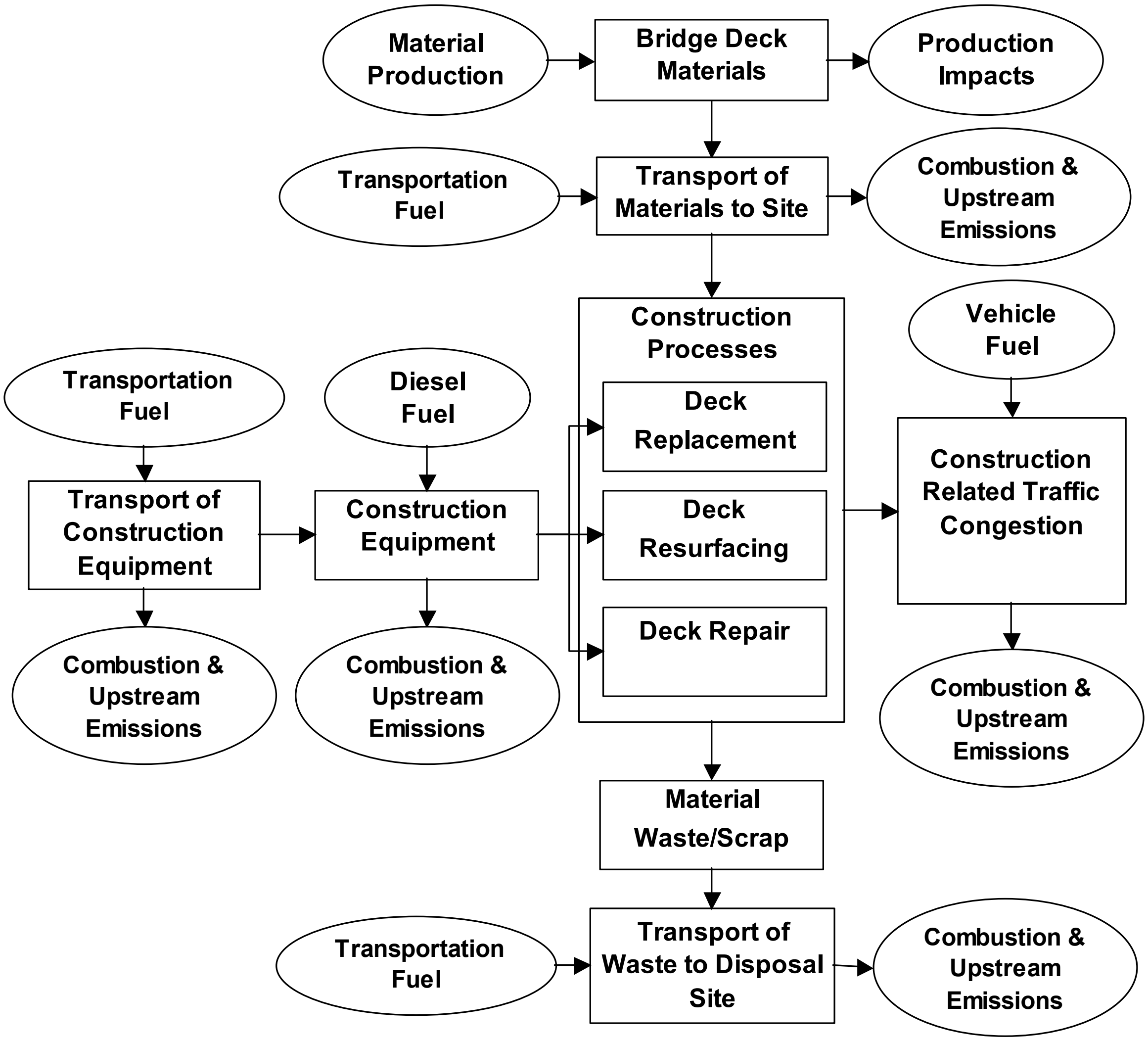


Figure 4. Diagram of System Boundary from Life Cycle Perspective

Modeling the complete life cycle of a single product or process is complex and data-intensive. Modeling the LCA of a more complex system, such as the concrete overpass described above, requires a modeling approach that can manage a long-lived system and respond to changes in many system parameters and provide sensitivity analysis to assess uncertainty in model parameters and assumptions. In the case of a highway overpass, life cycle modeling is complicated because the lifetime of the bridge is long; the timing and specifications of construction events, especially those that are decades in the future, can only be estimated; and the parameters controlling traffic and congestion are uncertain. An added uncertainty in this model is the incorporation of novel materials and designs. While the mechanical properties of these new materials are well studied and understood, empirical evidence of their behavior over time is simply not available.

2.4 Life Cycle Inventory

The first stage of the LCA is creating a life cycle inventory (LCI) for the system modeled. The LCI consists of the aggregated life cycle data for all of the energy and material inputs, and outputs from the product system. In this case, the LCI consists of the total aggregation of data over the bridge's 60-year life. This means each material, energy source, and transport mode must have an LCI dataset that describes its upstream burdens. Upstream burdens are those that accrue prior to the use phase, such as raw material acquisition and manufacturing or processing of materials. The LCI datasets and their details are discussed further in the Materials section, section 4.1.

2.5 Goals of LCA Model Development: An Integrated Life Cycle Design Framework

As stated in section 1.1.3, this report is the result of an interdisciplinary collaboration that integrates macro-scale modeling with microstructure level materials science in order to assess and improve the performance of advanced materials in infrastructure applications from a sustainability perspective. Figure 5 below is a diagram of the relationship between the macro-scale modeling and microstructure tailoring. The figure shows two process loops, "A" and "B". Traditionally these two loops operate independently from one another. However, their integration results in feedback between the processes of material design and life cycle modeling. By integrating the two, material designers can work to optimize material formulations based not only on material performance, but also on large-scale sustainability indicators founded on environmental, social and economic factors.

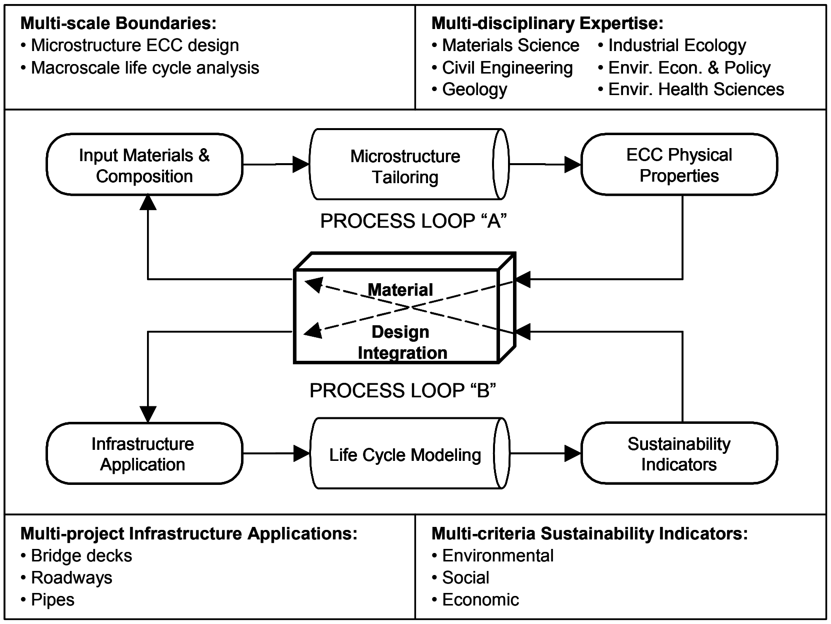


Figure 5. Integrated Materials Design Framework for Sustainable Infrastructure

This thesis focuses on developing and quantifying the environmental sustainability indicators in process loop "B". Feedback from the LCA model provides the material designers with information that helps move ECC formulations towards "greenness". Green formulations are those that substitute some of the more environmentally and energy intensive materials with less intensive materials like byproducts or wastes from other industrial processes. The idea is that through iterations in material formulations and their associated LCA, an optimal formulation for ECC can be developed that balances ECC link slab performance and the extent to which green materials are incorporated in its formulation.

2.6 Previous Research

In the case of concrete bridges, only a limited number of LCA's have been performed and published. Horvath and Hendrickson (Horvath and Hendrickson 1998) applied economic input-output life cycle assessment (EIO-LCA) to evaluate and compare steel and steel reinforced concrete bridge girders. The EIO-LCA method traces economic transactions throughout the supply chain of a product system and evaluates resource requirements and environmental emissions using a commodity input-output model coupled with key environmental impact datasets. Horvath and Hendrickson's analysis focused on material production, girder maintenance and end-of-life management activities. They concluded that steel reinforced concrete girders were preferable to steel girders, but the rate of recycling and incorporation of recycled steel in the girders could affect these results.

In contrast, the model described in this paper employs process level LCA methods to a more extensive system boundary that encompasses the interface between the material elements of the bridge deck and the roadway's users. The expanded system boundary results in a more comprehensive environmental assessment for material selection. Of the two bridge deck systems compared, the ECC link slab design is costlier from an initial material and cost standpoint. However, greater initial investment may be merited from a life cycle perspective.

While LCA methodology has rarely been applied to evaluate roadway systems, key road building materials and their applications such as asphalt pavement (Franklin Associates 2001) have been evaluated. Nevertheless environmental LCA is not often incorporated in the decision making process of road building and repair. Life cycle costing (LCC), however, has become increasingly important in transportation funding and projects. (FHWA 1998) While LCC focuses on the life cycle costs of projects, its growing role in transportation dialogues highlights that decision-makers have begun to recognize the need for more holistic ways of thinking about investing in roads and highways. This may signal a new paradigm in infrastructure planning that will be more open to accepting environmental LCA as a decision-making tool.

A broader array of literature exists for LCC modeling of concrete bridges than for LCA modeling. Previously developed life cycle costing methods, such as those published by M. A. Ehlen include agency and user costs (driver delay, vehicle operating and vehicle accident costs) and third party costs (Ehlen 1997). Ehlen classified third party costs as the upstream environmental costs associated with construction materials (pollution from mining, processing, and transportation) and the downstream environmental costs related to construction activities such as runoff (Ehlen 1997). While the increasing importance of third party costs were noted, they were not quantified and environmental impacts from construction related traffic delay were not identified in

Ehlen’s LCC model. A more holistic approach was taken in a thesis by Richard Chandler entitled “Life-Cycle Cost Model for Evaluating the Sustainability of Bridge Decks: A comparison of conventional concrete joints and engineered cementitious composite link slabs” (Chandler 2004). This thesis was based on results produced by an earlier version of the LCA model described in this thesis. Chandler’s thesis was far-reaching in its analysis, quantifying social, environmental, and user and agency costs. His results showed that costs incurred by road users during congestion dominated all others. This shows the need for improved integration of expanded life cycle costing methods that look beyond conventional costing and examine social and environmental costs as well.

The key distinction between Chandler’s LCA model and the one described in this thesis is his more frequent repair rate for both the ECC and conventional systems. Chandler’s conclusions were unequivocal and, since the models are otherwise similar, are suggestive of results expected for this LCA model.

3 Model Design and Framework

3.1 Model Structure

The LCA model is Microsoft Excel-based and runs six different workbooks using 12 Visual Basic Macros. Macros are programs written in Visual Basic (VBA) that are run within Microsoft's Excel software. The *LCA_main* workbook is the hub of the model and provides and receives information from the five others; *traffic*, *construction*, *materials*, *distribution*, and *end-of-life*. *LCA_main* houses the basic assumptions, the majority of user-input requirements, the key command macros, and the final inventory output for the entire model. The Figure 6 below shows the flow of command through the macro hierarchy. The figure shows the order in which the VBA macros are run; when data and information are retrieved from Excel spreadsheets and two look-up tables containing MOBILE6.2 and NONROAD data, and which workbooks retain calculation results:

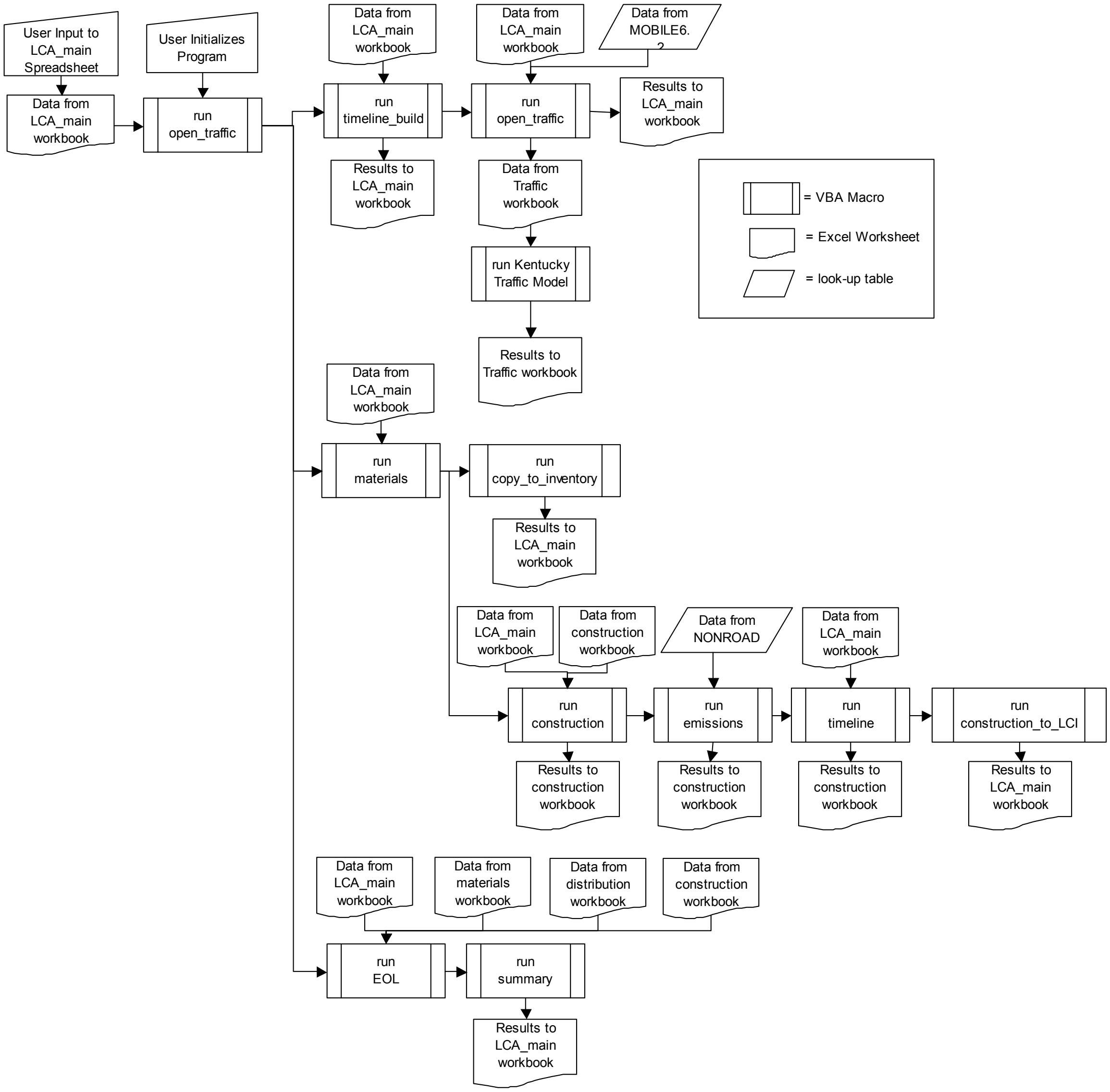
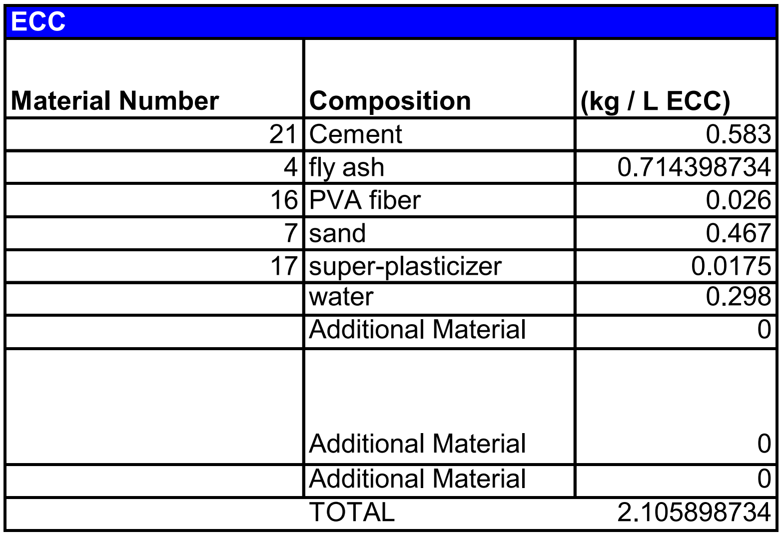


Figure 6. Computer Model Architecture

The model is capable of evaluating up to four different material formulations and two different bridge design scenarios at once. The bridge must either be a conventional mechanical steel expansion joint design or link slab design, but the details of these designs, such as the volume of any materials used, can be altered. All designs can involve different repair and reconstruction timelines. These timelines are key modeling assumptions for evaluating life cycle performance. Figure 7 is an example of a material formulation input table. The material number links the composition materials to the datasets associated with them. Cement, for example, has four different datasets associated with it based on the type of production facility, which can be either wet process, dry process, dry process with pre-heater, or dry process with pre-heater and pre-calciner. Any four of these can be modeled by changing the material number. The material numbers and material composition names flow through the rest of the model to ensure consistency throughout. Note that additional materials may be added and only require a name, material number, and fractional content in kg/L.



ECC		
Material Number	**Composition**	**(kg / L ECC)**
21	Cement	0.583
4	fly ash	0.714398734
16	PVA fiber	0.026
7	sand	0.467
17	super-plasticizer	0.0175
	water	0.298
	Additional Material	0
	Additional Material	0
	Additional Material	0
	TOTAL	2.105898734

Figure 7. Example of a Material Formulation Input Table

The remaining key inputs for users require defining material usage in construction (mass of material required and scrap rate) for each type of construction event, the construction timeline for repair and reconstruction of the bridge deck system, and traffic data such as annual average daily traffic (AADT), roadway parameters that define capacity, and typical versus construction posted maximum speed. These input requirements are discussed more thoroughly in the following sections specific to their application.

3.2 The Functional Unit

The functional unit boundary for this model is an existing concrete overpass undergoing its first bridge deck replacement. The life cycle accounts for the bridge deck and its interface with human users and builders over a 60-year time horizon, but not the initial construction of the bridge and its substructure. While the time horizon can be varied in the LCA model, it is constrained by the difficulty of performing comparative LCA on bridge deck systems with life times that do not share a common multiple within a reasonable time horizon. For example, if the conventional system is expected to last 42 years, and the ECC system 60-years, the first year when both systems will complete a life cycle and have no years of useful life remaining is at year 420. This time horizon is clearly not reasonable for assessing infrastructure applications of this kind. While choosing years of service such as 30 and 60 for the two systems cannot always be the case in real-world applications, the model currently does not have the capability to evaluate bridge deck systems whose life cycles are not equal or multiples of one another.

One alternative is to simply compare LCA results, but include remaining years of useful life for each system. To improve this measure, inventory results could be allocated based on the number of years evaluated. This would mean changing inventory results by some percent in order to reflect the number of years remaining or lacking based on the chosen LCA time horizon. Figure 8 depicts how these changes could be manifested. Box A. shows the scenario in this study, where the ECC system is expected to last 60 years and the conventional system is expected to last 30 years and is cycled through twice to meet the 60-year life of the ECC system. Box B. shows one way of managing a scenario where the two designs do not share easily reconciled lifetimes by applying the allocation method described above. The life of one system is truncated by some fraction such that the time lines are reconcilable. In this case the second 30-year life cycle of conventional system is truncated by 10 years. Applying the allocation method, the impacts of the second 30-year life cycle would be multiplied by 2/3.

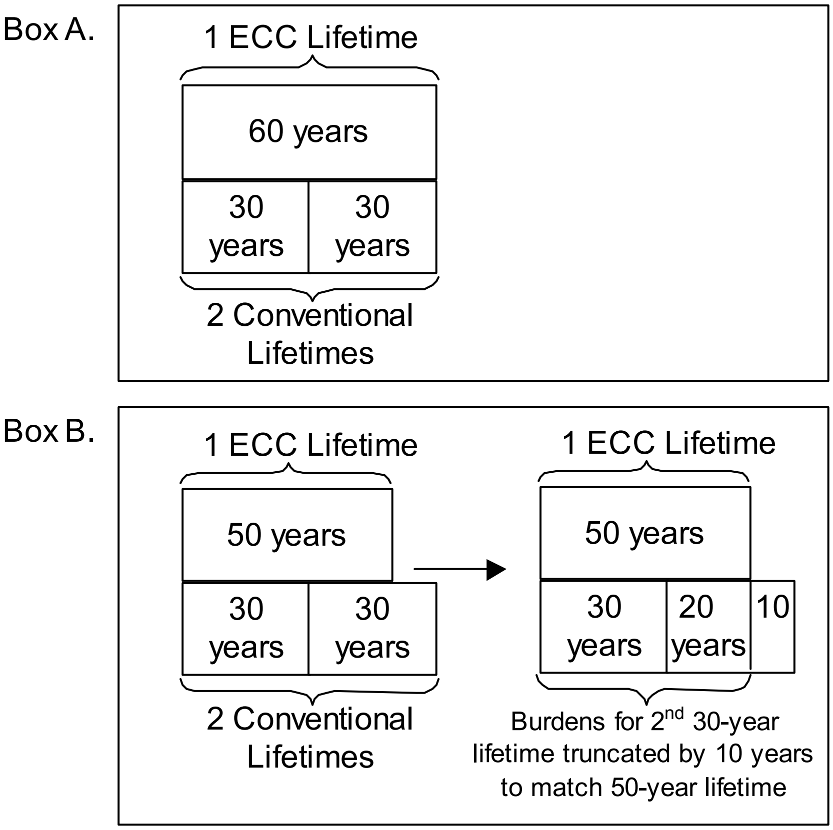


Figure 8. Alternatives for Managing Life Cycle Timelines

Drawing firm conclusions from the strategy shown in Figure 8, Box B may not be straightforward. Thus, based on judgments from engineering, and for the purpose of evaluation, the conventional deck was assumed to require replacement at 30 years, and the ECC at 60, making comparison tenable.

The definition of the functional unit explicitly means that inputs and burdens associated with the bridge's substructure are outside the scope of this model, despite that there are interactions between the deck and the substructure. Material inputs to the bridge deck, inputs required for repair and reconstruction, traffic congestion caused by construction events, and the distribution of inputs and waste from each of these elements are included in the model. While traffic congestion is measured and reported, the traffic that passes over the bridge on a daily basis is not directly reported in the model for three primary reasons. The daily traffic is assumed to be the same regardless of the bridge design selected, thus during non-construction periods in the use phase, the systems are considered identical. Additionally, the fuel use by trucks and automobiles that pass over the bridge everyday dwarf all the energy and air pollution associated with the other life cycle phases so reporting these values obfuscates other phases and impacts in the life cycle. The third and final reason is more philosophical than quantitative. The purpose of the model is to measure the life cycle impact of a bridge design decision. Regardless of the bridge design chosen, daily traffic will continue to pass over the bridge. Thus, the design impact is independent of daily traffic flow except when the design impacts the flow, such as during construction events. Thus, the appropriate way to represent the impact of construction periods is to measure how it *differs* from normal periods of traffic flow. Throughout the model and this thesis, traffic impacts refer to quantities as the difference between construction period traffic flow and normal, or baseline, flow.

3.3 Bridge Deck System Timeline

While the time horizon for modeling is set at 60-years for both bridge deck systems, the events occurring throughout are different for each system. The time pattern of these events has significant impact on LCA results. A key assumption in the model is that the ECC link slab design extends the life of the bridge deck surface, extends the life of the bridge deck as a whole, and reduces the frequency of pothole patching required. Moreover, the ECC slabs themselves are expected to last 60-years without needing replacement. Table 1 below shows the proposed timeline for the ECC link slab system and the conventional joint system:

Table 1. Timeline for Bridge System Construction Events

Construction Event	Construction Event Description		Interval (# Years)	
	Conv.	ECC	Conv.	ECC
Deck Replacement	Includes top 10 inches of deck and joint replacement	Includes top 10 inches of deck and ECC link slabs	30	60
Deck Resurfacing	Includes top 2 inches of deck and joint replacement	Includes top 2 inches of deck only	15	20
Repair and Maintenance	pothole patching	pothole patching	5	10

4 Computer Modeling of LCA Phases

The model design reflects the major life cycle phases outlined in the LCA framework. Therefore the model is broken down into five main computational modules; materials, construction, traffic, distribution and end-of-life. Each one is discussed in the following chapter.

4.1 Materials

To characterize material usage, the two different bridge designs have to be defined as well as the material formulations for steel reinforced concrete (SRC) and engineered cementitious composites (ECC). The bridge designs evaluated are a conventional design based on an SRC deck with mechanical steel expansion joints and an innovative design using an SRC deck with ECC link-slabs in place of the mechanical joints. In both cases the primary material used in the deck is concrete, in the form of SRC slabs. The slabs are joined together either by mechanical steel expansion joints in the conventional system or ECC link slabs in the alternative system. This section focuses on the materials used in the bridge deck, their constituents, their major environmental impacts, and how their usage is modeled in the LCA.

Of primary importance in the materials analysis are the life cycle datasets applied throughout the modeling process. Key datasets were provided by a number of sources including the Portland Cement Association (PCA), Ecobilan, and the International Iron and Steel Institute (IISI). Table 2 below shows data source details for the 12 primary materials used in the two bridge systems, the mass of each material used in each bridge design and throughout the 60-year life cycle, and the material's energy intensity. The quality of these datasets is discussed further in Section 5.

Table 2. Materials Data Sources in the Conventional and ECC Bridge Deck Systems and Associated Data Sources

Material	Conv. System		ECC System		Unit	Energy Intensity (MJ/kg)	Source of LCI Information
	Mass in Bridge Deck	Life Cycle Bridge Deck	Mass in Bridge Deck	Life Cycle Bridge Deck			
Portland Cement	242	608	233	327	Metric tonnes	4.5-6.6	Portland Cement Association (PCA 2002) and Ecobilan (Ecobilan, 2001) cement data, 1996
Gravel	480	1203	368	553	Metric tonnes	0.067	Portland Cement Association (PCA 2002), adjusted with electricity and fuel production from Ecobilan (Ecobilan, 2001). Original Ecobilan sources: Various, 1985-94. Equipment emissions from US EPA's NONROAD (US EPA 2000)
Sand	335	840	295	425	Metric tonnes	0.067	
Fly Ash	0	0	58	58	Metric tonnes	0	Only solid waste is accounted for as a negative value because it is diverted from the waste stream. Grinding and transportation of the fly ash is not accounted for.
PVA Fiber	0	0	2124	2124	kg	101	Industry Source and polyethylene data from Association of Plastic Manufacturers in Europe (Bousted 1999)
Super Plasticizer	0	0	1429	1429	kg	35	Formaldehyde data as surrogate for super plasticizer (Ecobilan, 2001). Primary Ecobilan source: Swiss Agency for the Environment, Forests and Landscape, 1994
Section Steel	377	754	377	377	Metric tonnes	9.5	International Iron and Steel Institute (IISI 2000)
Rebar Steel	31	63	31	31	Metric tonnes	8.4	International Iron and Steel Institute (IISI 2000)
Epoxy	22	45	22	22	kg	80	Ecobilan (Ecobilan 2001). Primary Ecobilan source: Perrin and Scharff, 1993.
Rubber	88	353	0	0	kg	84	Ecobilan (Ecobilan 2001). Primary Ecobilan sources: Various, 1985-89.
Wood	29	58	0.6	0.8	Metric tonnes	28	Ecobilan (Ecobilan 2001). Primary Ecobilan source: Western Wood Products Association (WWPA), 1995.

4.1.1 *Concrete*

Concrete is ubiquitous in developed human environments. Its primary constituents; portland cement, course and fine aggregates, water, and air, are widely and economically available. Concrete's attractiveness is partly the result of its chemical properties that allow it to be poured as a liquid and cured into a rigid solid, making building easier than with other material. Despite its wide use, concrete's brittleness and tensile weakness limits its durability in many applications. In many cases, such as bridge deck applications, SRC is used instead by laying steel reinforcing bar within concrete forms to improve tensile strength and reduce brittleness. Despite these additions, the limiting factor in concrete durability is still its brittleness.

Table 3 shows the concrete formulation used in the LCA model. The formulation is based on Michigan Department of Transportation (MDOT) standards for concrete. (MDOT 2003)

Table 3. Conventional Concrete Formulation

Composition	g/L Concrete
Air	0.05
Cement	474
Gravel	938
Sand	655
Water	200

4.1.2 *ECC*

ECC is a unique fiber-reinforced material with a microstructure design driven by micromechanical principles (Kanda and Li 1998; Li 1998). Unlike other concrete materials, ECC strain-hardens after first cracking, similar to a ductile metal, and demonstrates a strain capacity 500-600 times greater than normal concrete, eliminating much of the tensile weakness and brittleness exhibited in conventional concrete formulations (Li and Stang 1997). Other characteristics of ECC include a fracture toughness like that of aluminum alloys (Maalej et al. 1995), extreme damage tolerance (Li and Stang 1997) and ductility under severe shear loading conditions (Li and Chan 1994). ECC formulations are designed through microstructure tailoring of matrix, fiber and fiber-matrix interfacial elements. ECC contains ingredients similar to fiber-reinforced concrete (e.g., water, cement, sand, fiber, and superplasticizer) but not course aggregates like gravel. Table 4 shows the ECC formulation applied in this LCA model. ECC researchers at University of Michigan's Advanced Civil Engineering Materials Research Laboratory supplied the material formulation.

Table 4. ECC Material Formulation

Compostion	g/L ECC
Cement	583.0
Fly Ash	714.4
PVA Fiber	26.0
Sand	467.0
Superplasticizer	17.5
Water	298.0

The addition of PVA fiber and superplasticizer, and the omission of course aggregates means that inputs to ECC are more energy intensive on a per-volume basis than conventional concrete formulations. Figure 9 illustrates the difference in total primary production energy between ECC and SRC for a metric tonne of material. Total primary energy includes the upstream burdens associated with material production such as raw material extraction, fuel production, and distribution burdens. The figure assumes that concrete uses 1% rebar by weight for concrete. The total life cycle energy for concrete and ECC is 3420 and 7100 MJ per metric tonne respectively. For concrete 91% of the total energy consumption is from cement, whereas, for ECC only 54% of consumption is from cement, and 37% results from the PVA fiber content.

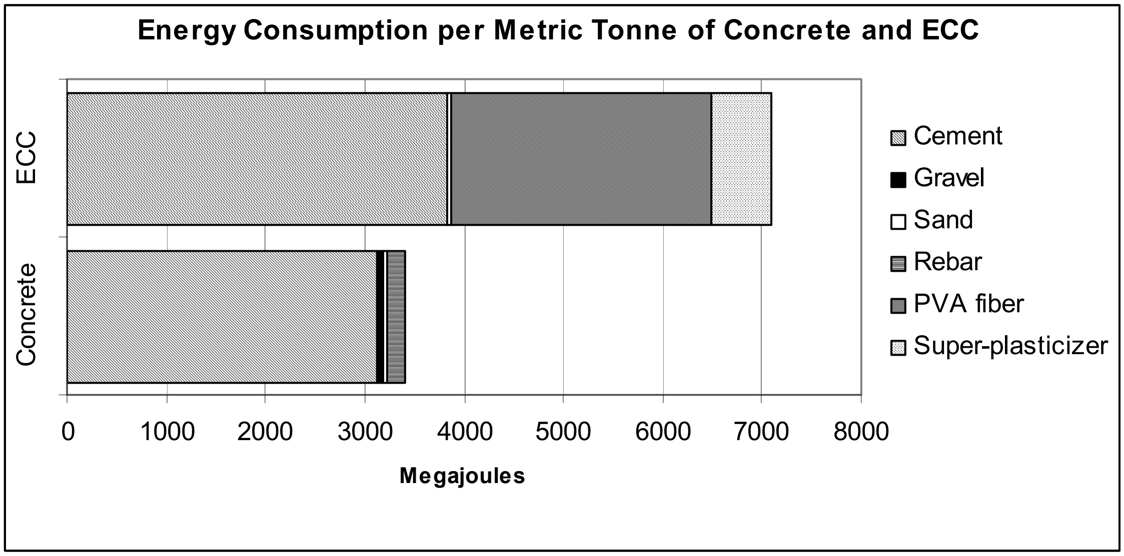


Figure 9. Energy Consumption per Metric Tonne of Conventional Steel-Reinforced Concrete and ECC

While the ECC material is more energy intensive, the ECC link slab bridge design only contains ECC in the slabs, the rest of the deck is still comprised of conventional concrete. This means that the significant difference in material energy intensity shown above is somewhat muted in the overall bridge design. For example, ECC is more than twice as energy intensive per unit of mass, but the material energy in the overall ECC bridge deck design is only about a third more than the conventional design.

4.1.3 *Cement*

Cement is the major contributor of material production energy in both ECC and conventional concrete. The cement production process begins with raw material acquisition, namely limestone quarrying, and is followed by an industrial process that produces clinker, the precursor to cement. To create clinker, limestone, or other calcium carbonate material, is mixed with a silica material, then ground, and heated in a kiln. The initial phase of kiln heating drives CO_2 from the limestone, and further heating results in a number of complex chemical reactions in the materials. This process requires a great deal of heat, which is an additional source of CO_2 since it requires fuel burning. Figure 10 below shows a typical cement production flow chart.

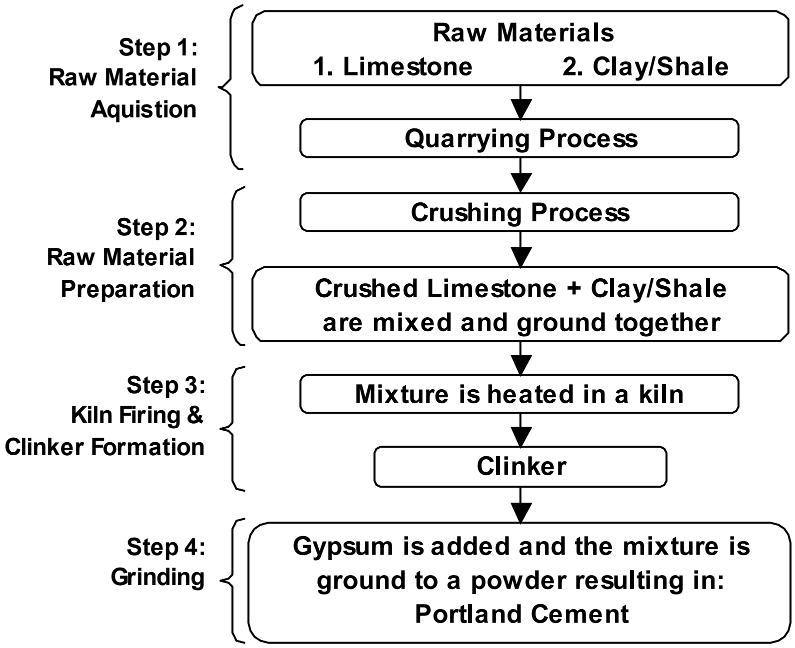


Figure 10. Cement Production Flow Chart
[Adapted from: (Chamberlain et al. 2004)]

Step 3 in the diagram above, kiln heating, is one of the most energy intensive processes in cement production. A number of alternative kiln configurations exist, all of varying degrees of efficiency. The most significant difference between kiln types is the wet and dry processes. In wet process kilns the raw materials are slurried prior to entering. This means a greater amount of energy is needed since the water used to slurry the materials must be evaporated during the heating process. In the dry process materials enter the kiln dry, and thus the kiln heat goes directly towards heating the raw material. In general, wet process kilns only exist in older plants that have not yet been updated with the improved dry process systems.

The possible permutations for kiln technology configurations are based on the following options: the process can be a wet or dry process, have a pre-heater, and a pre-calciner. Table 5 shows the total life cycle production energy for the conventional and ECC bridge deck systems based on the production energy requirements of the different processes. The LCA assumes the wet process is used since it is what is regionally available and thus the likeliest production mode for the cement modeled in this LCA. Clearly, there are potential energy savings to be gained if production modes were to be changed.

Table 5. Kiln Configurations and Total Primary Energy per Kilogram of Cement Produced

[Data provided by the Portland Cement Association **(Nisbet et al. 2002)**]

Kiln Type	Total Production Energy (MJ/kg cement)	% Difference from Wet Process
Wet Process	6.57	--
Long Dry Process	6.07	7.61%
Dry Process with Preheater	4.9	25.42%
Dry Process with Preheater and Pre-calciner	4.52	31.20%
Weighted US National Average	5.32	19.03%

4.1.4 *Modeling the Materials Phase*

The materials phase of the life cycle model is comprised of the material production and disposal processes involved in the bridge deck system. Figure 11 shows the boundaries of the materials module of the life cycle model, the items included in the module are boxed with a dashed line. Shown above the dashed box are the datasets and sources that supply life cycle inventory information for materials. This module essentially accounts for all of the materials used to construct the bridge deck, including those that result as scrap from the construction process. In all cases the distribution of materials to the construction site, and the distribution of waste materials from the construction site are considered distribution and end-of-life processes.

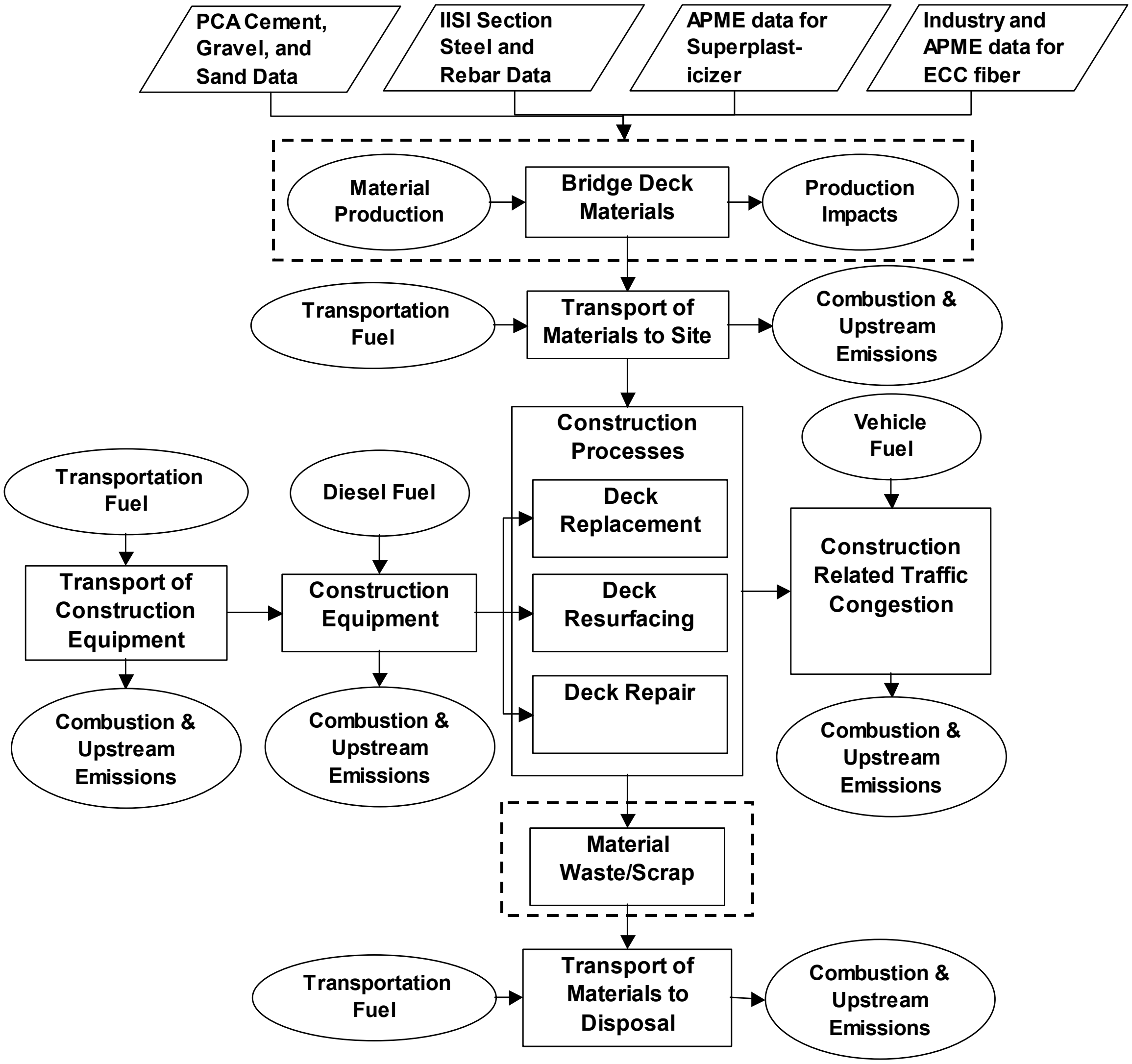


Figure 11. Life Cycle Model Boundary Diagram – Materials Module

A computer program module was developed to model the materials portion of the bridge deck life cycle. Two macros, "materials" and "copy_to_inventory" run this module of the LCA model. The "materials" program relies on user inputs to the

LCA_main spreadsheet defining bridge deck volume, the volume of steel expansion joints or link slabs, construction scrap rate, and the timeline for repair and reconstruction. The timeline is a key determinant of the bridge deck system's life cycle performance. Timeline specifications were developed based on information provided by participating engineers, MDOT, and construction contractors.

As shown in Figure 11, there are three construction events that occur over the life cycle of the bridge deck: deck replacement, deck resurfacing, and repair and maintenance. The first two construction events are different in the link slab and conventional systems. In the case of the ECC link slab system, a deck replacement includes installation of link slabs to a depth of 11 inches and SRC deck replacement to a depth of 10 inches. For a conventional joint system, deck replacement includes installation of new joints surrounded with a concrete depth of 11 inches and deck replacement to a depth of 10 inches. Table 6 below shows the different volumes of key materials used in these construction events. A detailed inventory of material demands for each type of construction event is also available in Appendix A. Additional materials are needed for construction that are not part of the volumes shown here, such as wood used in making concrete forms. The usage of additional materials is also included in Appendix A.

Table 6. Volume of SRC, ECC, and Steel Required in Construction Processes

		Deck Replacement (L)	Deck Resurfacing (L)	Patching and Repair (L)
ECC Link Slab System	SRC	414528	82906	2500
	ECC	80467	--	--
SRC Steel Joint System	SRC	488125	3585	2500
	Steel	2822	2822	--

Table 6 above suggests that the rate of repair and reconstruction events could impact model results since any repeat of a resurfacing or replacement process would mean a much greater life cycle material investment. An example of the construction timeline is shown in Figure 12. As with many of the parameters in this model, the timeline can be changed to reflect changes in assumptions regarding the life of the bridge deck, the durability of repairs, and for sensitivity analysis. Note the considerably higher frequency of repair and reconstruction on the conventional system, and thus increased material investment.

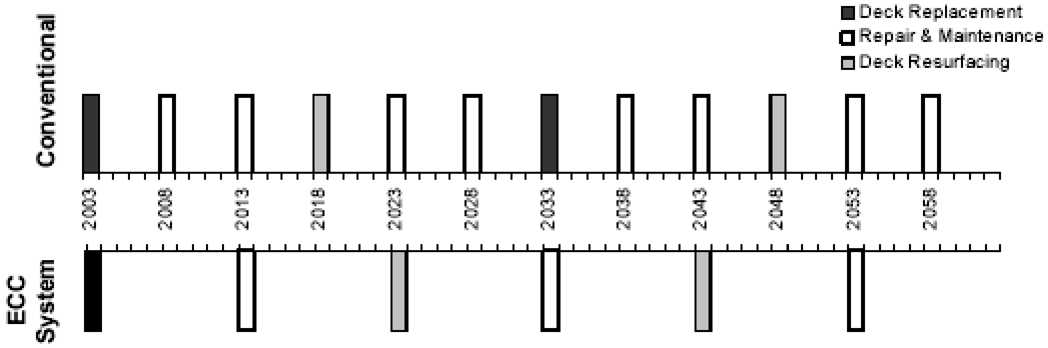


Figure 12. Construction Event Timeline

The timeline assumes that a full 60 years of life remain for either bridge deck system when the first deck replacement occurs. Currently, in this model the comparison between bridge deck designs is only possible if both decks are assumed to become obsolete at the same time. The assumption is clearly not valid under all circumstances, but for the purpose of this model it is assumed to be so. While the most convenient timeline definition assumes regular, periodic repair rates, the timeline applied in the model can also be manually adjusted for non-periodic events by the user if need be.

4.1.5 *Macro Logic Sequence*

The following steps outline the logic sequence for the materials module.

1. From *LCA_main* workbooks verify which of the four possible SRC and ECC material formulations are to be analyzed in the run.
2. Appraise timeline information to create construction plan for each bridge system's life cycle.
3. Using detailed construction site material needs and scrap rates from the *LCA_main* workbook build a material usage calendar based on the year of construction and the type of construction event. This step in the data transformation is re-used to calculate burdens in the distribution phase of the model.

4. Create an output spreadsheet that multiplies inventory datasets by total mass of each of the different materials used in a given year.
5. Export data from *Materials* workbook to *LCA_main* "Life_Cycle_Flows" worksheets.

4.2 Construction

The construction module for the LCA model is significantly more complex than the materials module. The construction process has two major environmental impacts beyond material use and disposal, namely construction equipment use and traffic congestion caused by the construction zone. The traffic congestion is dealt with in the traffic module. The area boxed in with a dashed line in Figure 13 delineates the life cycle model concepts that are included in the construction module.

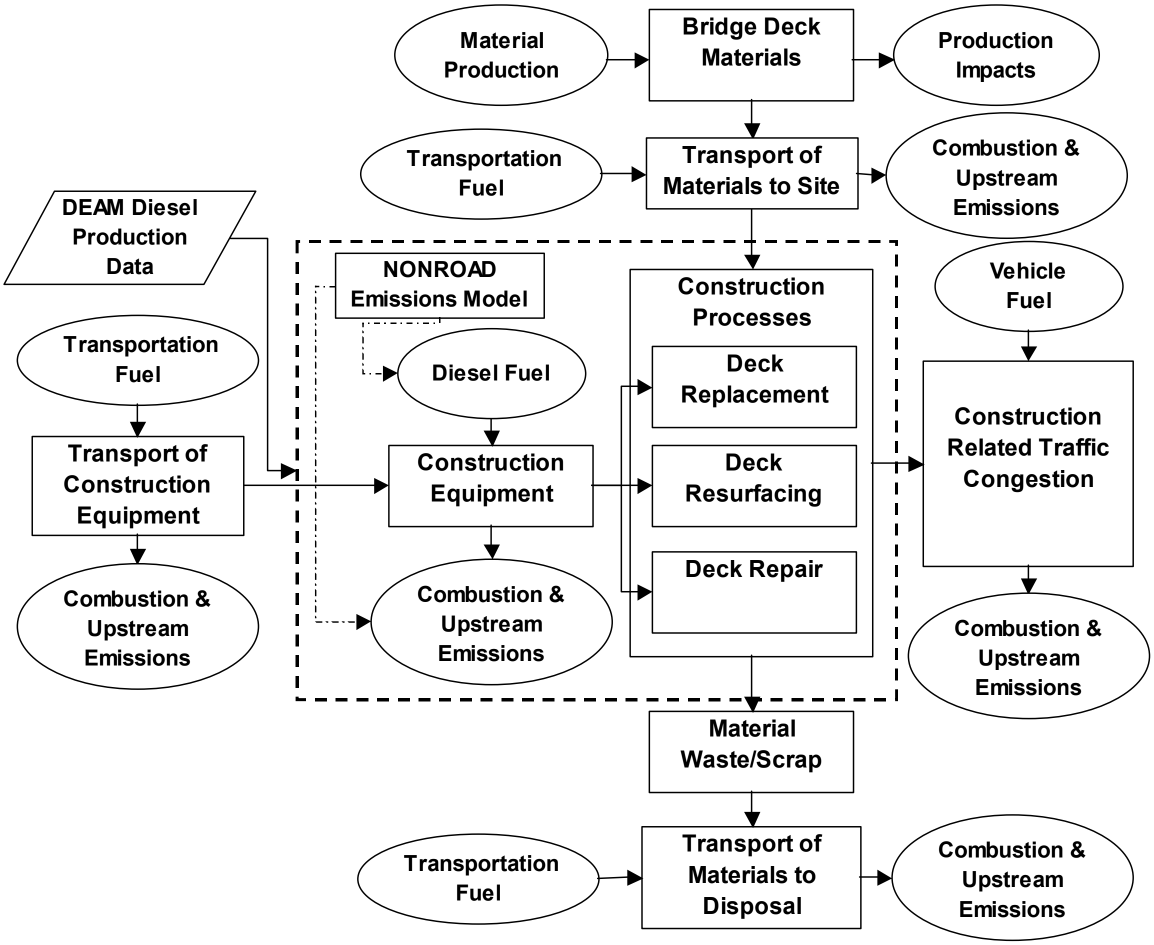


Figure 13. Life Cycle Model Boundary Diagram – Construction Module

Construction is handled within the LCA model in its own workbook. Output from computations in this workbook include, combustion-related air emissions from equipment use, quantity of fuel burned, the upstream burdens of this fuel, and the weight of the equipment. While equipment weight does not impact calculations in this LCA phase, the data are necessary for calculations in the distribution phase since the equipment has to be transported to the construction site.

Mobile sources of emissions account for a considerable portion of the total air emissions released in the U.S. Mobile sources include road-based sources such as automobiles, and non-road sources from equipment used in construction, logging, agricultural, and other off-road operations. While emissions from roadway traffic generally dominate mobile emissions sources, some regions of the country are estimated to incur more than a third of these emissions from non-road sources ((ENVIRON

International Corporation 2002); thus, modeling non-road emissions is essential in estimating the total impacts of bridge design and material choice.

The US Environmental Protection Agency's (EPA) NONROAD model was selected as a tool to estimate fuel use and emissions from construction equipment based on vehicle class and horsepower rating. NONROAD is still in its draft phase, and as such cannot be considered with the full weight of confidence that goes with an approved EPA model. Nevertheless, the NONROAD model is the most advanced tool available for this type of calculation.

NONROAD is driven by a core program that runs in FORTRAN and a user interface that runs in Visual Basic. While numerous input factors can be selected for deriving output data, the data used for this LCA model was calculated based on the region of use and selected by machine type defined by an equipment code and horsepower class.

Construction activities are broken between end-of-life (EOL) and construction processes. Those processes that involve demolishing and dismantling of bridge components and removal of demolished materials from the construction site are designated as EOL. All others are processes are designated as construction. In the final LCA model results, the burdens associated with EOL processes from this phase are presented as EOL, rather than construction. Since traffic controls are set-up and removed only once from the construction site during any event, the initial traffic control set-up is allocated to EOL because EOL is the first step in reconstruction events, and the removal of traffic controls are allocated to construction.

Table 7 shows the construction machinery requirements for construction events associated with the conventional joint and ECC link slab bridge designs. These equipment requirements are based on estimates from a Michigan-based highway contractor. The model is flexible with regard to equipment needs. Additional machinery requirements for an event can be added and current ones can be altered or deleted and in all cases estimated hours and days of usage can be changed.

Table 7. Equipment Usage During Construction Activities

Equipment	hp rating	Equipment Usage (hrs / construction event)				
		Conventional system deck replacement and joint replacement	ECC system deck replacement and link slab replacement	Conventional system resurfacing and joint replacement	ECC system resurfacing	maintenance and repair
Crawler-mounted hydraulic excavator	428	128	128	0	0	0
Air Compressor	350	64	128	48	0	0
Concrete Mixer	8	0	0	0	0	16
Concrete Paving Machine	250	96	32	32	32	0
Concrete Truck	300	32	32	32	32	0
Crane, 50 ton	177	176	176	0	0	0
Dumper	23	128	192	80	32	0
Hydraulic Hammer	100	64	128	0	0	0
Motor Grader	165	0	0	16	16	0
Signal Boards	6	18000	24480	7680	4992	0
Vacuum Truck	177	0	0	32	32	0
Water Truck	450	0	0	32	32	0
Wheeled Front-end Loader	235	624	688	48	0	0

To facilitate speed and convenience in using the LCA model, NONROAD output was converted into look-up tables based on year of use, machine type, and horsepower class. The construction macro, after identifying the machinery used for a specific event, matches the year of the event, equipment code, and horsepower class with emissions values in the NONROAD look-up table. These emissions are then multiplied to match the total usage time in horsepower-hours for the machinery and expressed as output to the LCA inventory. NONROAD's emissions categories are limited; however, users can choose from a number of ways for the model to output hydrocarbon data. For the purposes of this LCA Model the following output categories from NONROAD are used:

Table 8. NONROAD Output Categories Selected for LCA Model Use

Output Category	Unit
Total Hydrocarbons (THC)	g/hp-hr
Carbon Monoxide (CO)	g/hp-hr
Nitrogen Oxides (NO_x)	g/hp-hr
Carbon Dioxide (CO_2)	g/hp-hr
Sulfur Oxides (SO_x)	g/hp-hr
Particulate Matter less than 10 µ (PM_{10})	g/hp-hr
Fuel Consumption (Diesel)	L/hp-hr
Aldehydes	g/hp-hr
Methane (CH_4)	g/hp-hr
Ethane (C_2H_6)	g/hp-hr

While NONROAD supplies the estimated fuel consumption for machinery usage, the upstream burdens associated with this fuel are not accounted for. The LCA reference dataset for diesel fuel is applied to the values for fuel consumption derived from NONROAD.

4.2.1 *Macro Logic Sequence in Construction*

The following steps outline the logic sequence for the four construction module macros, "construction," "emissions," "timeline," and "construction_to_LCI."

1. From *LCA_main* workbook verify which of the four possible SRC and ECC material formulations are to be analyzed in the run.
2. Collect machine use information for each required construction event from *Construction* workbook. Information needed includes machine number (equipment number, class, horsepower rating, and year of use), machine weight (for use in *Distribution* calculations), hours of usage, and whether the process is EOL or construction.
3. Use NONROAD data look-up pages to match machine number and record emissions values based on hours of usage.

4. Copy and reformat results from *Construction* workbook into *LCA_main* inventory worksheets based on sub-processes within each type of construction event to ensure that construction output data can be allocated between EOL and construction burdens.

4.3 Traffic

The traffic phase of the life cycle analysis focuses only on traffic related to construction processes. The dashed-line box in Figure 14 shows the portion of life cycle modeling that is calculated in the traffic module. There are two important features of this module evident in the figure below. The first is that only traffic disturbances caused by construction events are accounted for in the model. These changes in traffic flow and congestion are modeled using the KyUCP traffic model (Rister and Graves 2002). The second important feature is the EPA's MOBILE6.2 model, used in this section to calculate combustion related emissions from traffic (USEPA 2002). MOBILE6.2 does not calculate vehicle fuel use; thus, the LCA model calculates fuel consumption based on speed of travel, vehicle type, and age for the fleet of vehicles on the road. Fuel economy figures are based on estimates from the US EPA (Hellman and Heavenrich 2003).

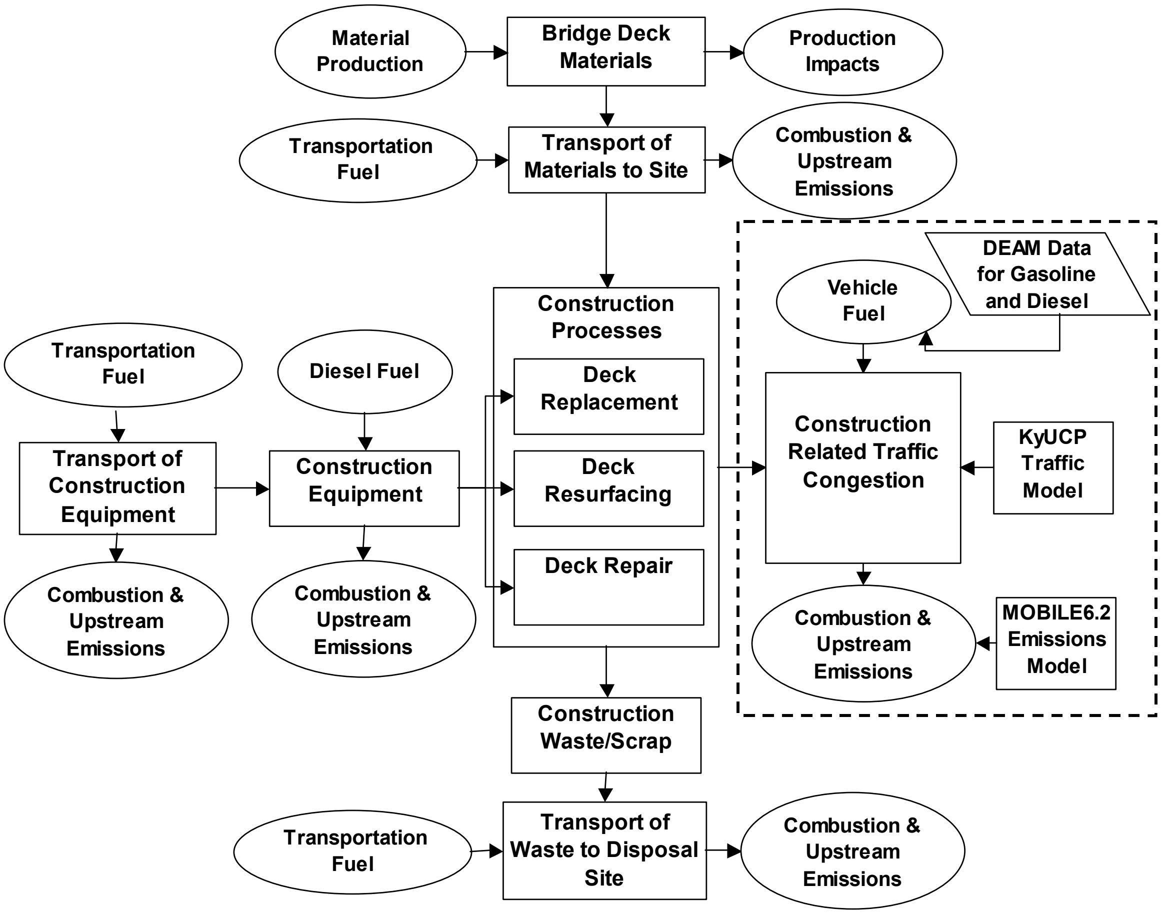


Figure 14. Life Cycle Model Boundary Diagram – Traffic Module

Traffic flow defines the use phase of the bridge deck life cycle. However, simply modeling the impacts of the traffic flow that passes over the bridge does not capture the interaction between the bridge deck and its users. The assumption is that, regardless of the bridge deck design, a certain volume of traffic passes over the bridge. Thus, the bridge deck itself impacts traffic in two key ways:

1. When the bridge deck goes under repair, traffic congestion results from delays over the construction work zone. This construction related delay results in additional fuel consumption and related emissions as well as economic burdens.
2. The roughness of the bridge deck surface can cause damage and wear to vehicles and reduce fuel economy, resulting in added costs to drivers and environmental burdens from additional fuel use, repair processes, and part manufacturing. (Morreti et al. 2003)

The second impact mentioned above cannot be feasibly modeled. While there is clear evidence that rough surfaces and potholes cause significant wear and tear to vehicles, quantifying the environmental impact is currently not possible. However, the first impact, delays related to construction, can be modeled. Comparing the modeled congestions to flow during non-construction (baseline) conditions, results in a value for the impact of construction activities on traffic flow. This difference is in effect the interaction between the bridge deck surface and vehicle traffic.

4.3.1 *Traffic Model Selection*

Traffic model selection is a key factor in this LCA since the use phase is highly dependent on traffic model output for calculating the burdens associated with this phase. A number of traffic models exist for modeling construction-related traffic delays, including QUEWZ98 developed at the Texas Transportation Institute, CO^3 developed by Robert Carr at the University of Michigan, QuickZone developed at the Federal Highway Administration (FHWA), and the Kentucky User Cost Program version 1.0 (KyUCP) developed at University of Kentucky's Kentucky Transportation Center. (Rister and Graves 2002) Each of these models had exceptional strengths. For example, the QUEWZ98 allows detailed detour routes to be included. However, in addition to demanding a lot of user input, this model runs in DOS and outputs in DOS, meaning that integration into the Excel-based LCA model proved difficult. Another model, CO^3, also proved difficult to integrate into this model as it is geared towards optimization of construction cost and construction congestion (Carr 2000). Final model selection was based on optimizing between the level of detail and traffic data demands, and the ease with which the model could be integrated within the LCA. The KyUCP model was chosen based on this selection criteria. This model, built from the DP-115 framework developed by the FHWA, is an Excel-based model that outputs user delay data and user cost data. Only the user delay output is incorporated into the LCA model.

DP-115 is the FHWA's Demonstration Project No.115, *Probabilistic LCCA in Pavement Design (DP-115)*. The goal of this project was to develop recommended life cycle cost assessment procedures for the national highway system (Walls and Smith 1998). In their September 1998 Technical Bulletin, the FHWA laid out the framework and calculations for the DP-115 demonstration model. The KyUCP model was developed from this framework, but incorporated the additional element of short-term versus long-term construction sites. One attractive feature of this model is the limited user input required; work zone capacity, work zone length, traffic flow rate based on either annual average daily traffic (AADT) or hourly traffic data, normal highway capacity, and percent of trucks on the road. Capacity calculations are based on the Transportation Research Board's Highway Capacity Manual (TRB 2000). Roadway capacity changes during construction events because lanes are shut down necessitating merges, speed is reduced, and because lane width may be reduced in the work zone. In the LCA scenario modeled, capacity reduction during construction resulted from lane shutdown and reduced speed, and normal highway capacity was correlated to lane width and speed limit.

4.3.2 *Vehicle Emissions*

Once vehicle delay and congestion due to construction are calculated, these results have to be coupled with fuel consumption and vehicle emissions data in order to measure environmental impact. The US EPA's MOBILE6.2 software was selected to compute estimates of vehicle emissions. (USEPA 2002) MOBILE6.2 takes climatic, temporal, and regional vehicle fleet data into consideration when estimating vehicle emissions at various speeds. Predictions are available from the MOBILE6.2 software on a per year basis through 2050. For years following 2050, the 2050 emission estimates are used. MOBILE6.2 requires inputs regarding the geographic region where the vehicles are driving. The geographic location, climate, and traffic flow for the bridge evaluated in this LCA model are based on an overpass in Washtenaw County, Michigan at the intersection of M-14 and US-23. The parameters provided for this bridge site include annual average daily traffic (AADT) flow, and climatic conditions (necessary for estimates in MOBILE6.2).

MOBILE6.2 output was recorded in look-up tables to facilitate speed and user friendliness of the LCA model. If the location of the modeled bridge changes, the MOBILE6.2 lookup tables would have to be updated to reflect this change.

MOBILE6.2 does not calculate carbon dioxide (CO_2) emissions or fuel consumption. This is a major shortcoming in the model given the magnitude of CO_2

emitted from automobiles and the growing concern over its role in global warming. In the LCA model an alternative mechanism for calculating these effects of construction related traffic congestion was devised.

4.3.3 *Fuel Consumption and Carbon Dioxide*

In addition to direct emissions from vehicles, the amount of excess fuel consumed as a result of delays was also calculated and the production and combustion of this fuel was accounted for. Fuel consumption for cars and trucks was determined based on city and highway drive cycle estimates of fuel economy. Data for cars came from US EPA fuel economy data (Hellman and Heavenrich 2003) and commercial truck data from The Technology Roadmap for the 21st Century Truck Program (Bradley 2000). A city drive cycle is the closest estimate of fuel economy available for modeling the stop-and-go movement typical of congestion. Likewise, a highway drive cycle for normal traffic flow is used to model flow during non-construction and non-congestion periods. The final results are calculated by subtracting emissions and fuel consumption during an equivalent non-construction period from the results of a construction period. The construction period results are the sum of the results from vehicles passing through the work zone length, queue length, and detour length. These values are based on the total vehicle miles traveled (VMT) at certain speeds.

The values for highway speed, highway capacity, work zone length, work zone capacity, work zone speed, and AADT can all be changed in the LCA model. The numbers used in this thesis are based on the real-world values associated with the selected overpass, which defines AADT at approximately 70,000, with two lanes in each direction, and a speed limit at 70 mph. (MDOT 1997). The work zone consists of one lane in each direction, and a speed of 40 mph.

Drivers are expected to self-detour under many delay conditions. That is, even when formal detour routes may not be used, many drivers will choose alternative routes if back up is expected. While some congestion models have the capacity to account for this behavior, the KyUCP model does not. In order to evaluate the importance of vehicle detouring, the LCA model can modify input values to the KyUCP model to account for detouring. The model is capable of computing up to three possible detour lengths, each at different speeds with different percents of vehicles on each detour. Sensitivity analysis was performed on differing percentages of detouring vehicles. In all cases, except where otherwise noted, detours are assumed to add 1.5 miles of driving at 40 mph, and approximately 12% of drivers self detour. This scenario is meant to represent detouring vehicles driving on suburban roads that approximately parallel the highway. The real world rate of motorists who choose to detour is essentially unknown; consequently, a sensitivity analysis of detouring and its relationship to transportation energy was done. Figure 15 below shows the change in traffic energy consumption as detour length and percent of vehicles detouring changes. Sensitivity analysis was run at detour lengths at the base case scenario of 1.5 miles, 2 miles, and 2.5 miles. The detour rate was varied at 12%, 10%, 5%, 2%, and 0%. The percent of detouring vehicles has a much more significant impact on energy consumption than the distance detoured.

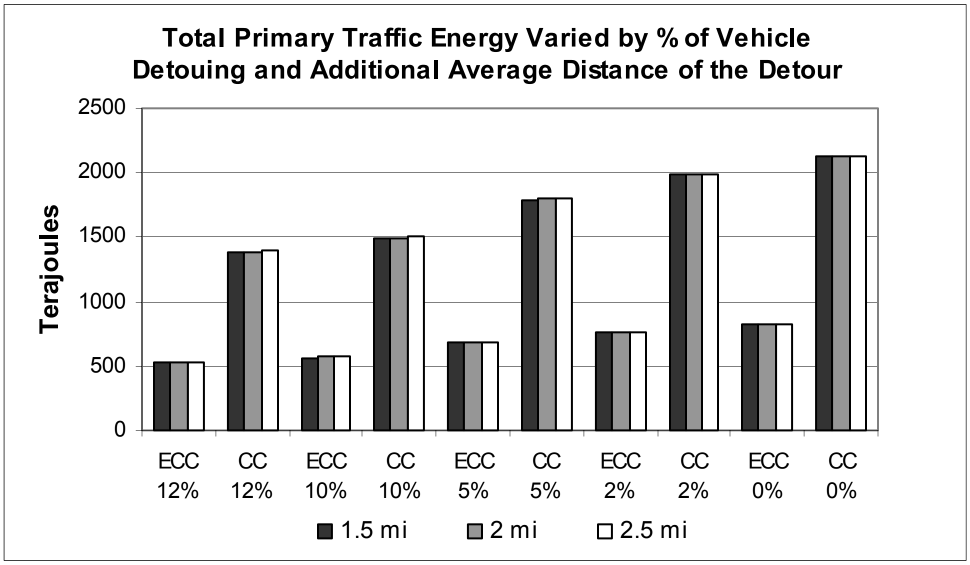


Figure 15. Change in Total Primary Traffic Energy with Detour Length and Percent Detour

A key assumption is that additional traffic on the detour roads does not cause congestion or back-up on those roads. Because the KyUCP traffic model cannot account for a vehicle detour scenario, the change in traffic volume over the bridge resulting from detouring vehicles is handled within the LCA model. The traffic model simply receives an input value for traffic volume that has already been reduced to reflect the detoured traffic. The vehicle miles traveled (VMT), fuel consumed, and vehicle emissions from detoured vehicles are added to the traffic phase of the LCA model during the vehicle emissions calculation phase, after the traffic model has been run.

The output from the traffic phase of the LCA model consists of values for fuel consumption, emissions, and time lost to travelers in congestion. All of these values are calculated based on their difference from the baseline condition of non-construction traffic flow. In all cases the following equation is applied to the parameter being calculated, such as emissions values (mg/mile), time (hour/mile), and fuel use (gal/mile). These parameters are multiplied by the VMT of each traffic condition, such as VMT in the traffic queue, or VMT through the work zone. The distance over which VMT is calculated for the baseline scenario changes with traffic queue length. In the equation below the parameters are represented by the variable "Y":

$$\text{Result (Y)} = (\text{VMT}_{\text{Queue}}{*}\text{Y} + \text{VMT}_{\text{Work zone}}{*}\text{Y} + \text{VMT}_{\text{Detour}}{*}\text{Y}) - \text{VMT}_{\text{Baseline}}{*}\text{Y}$$

4.3.4 *Macro Logic Sequence for Traffic*

The following steps outline the logic sequence for the traffic macros.

1. From *LCA_main* workbook verify which of the four possible SRC and ECC material formulations are to be analyzed in the run.
2. From *LCA_main* collect relevant user-input information such as length of each construction process, on-road vehicle fleet figures like percent trucks, speed limits for highway and work zone, detour figures, and the timeline of events.
3. Run the traffic model, housed within the *Traffic* workbook, for each event over the 60-year time horizon and copy output for each event into a single worksheet.
4. Use the output from step 3 to collect emissions data from the MOBILE6 look-up tables based on speed and year of event. This has to be done for the base case and the construction case for each event at each year.
5. Calculate fuel consumption and associated CO_2 values, calculate their difference from the baseline values, and add these to the output data.
6. Copy and paste vehicle emissions to *LCA_main*.

7. Use fuel consumption values to calculate upstream emissions from fuel use and paste into *LCA_main*.

4.4 Distribution

The distribution module is closely linked to the materials and EOL modules. All materials must be brought to the construction site and all waste materials hauled away. The diagram below shows the areas of the life cycle model that fall within the distribution phase. Ecobilan's DEAM database supplied the datasets used to calculate upstream burdens of fuel production.

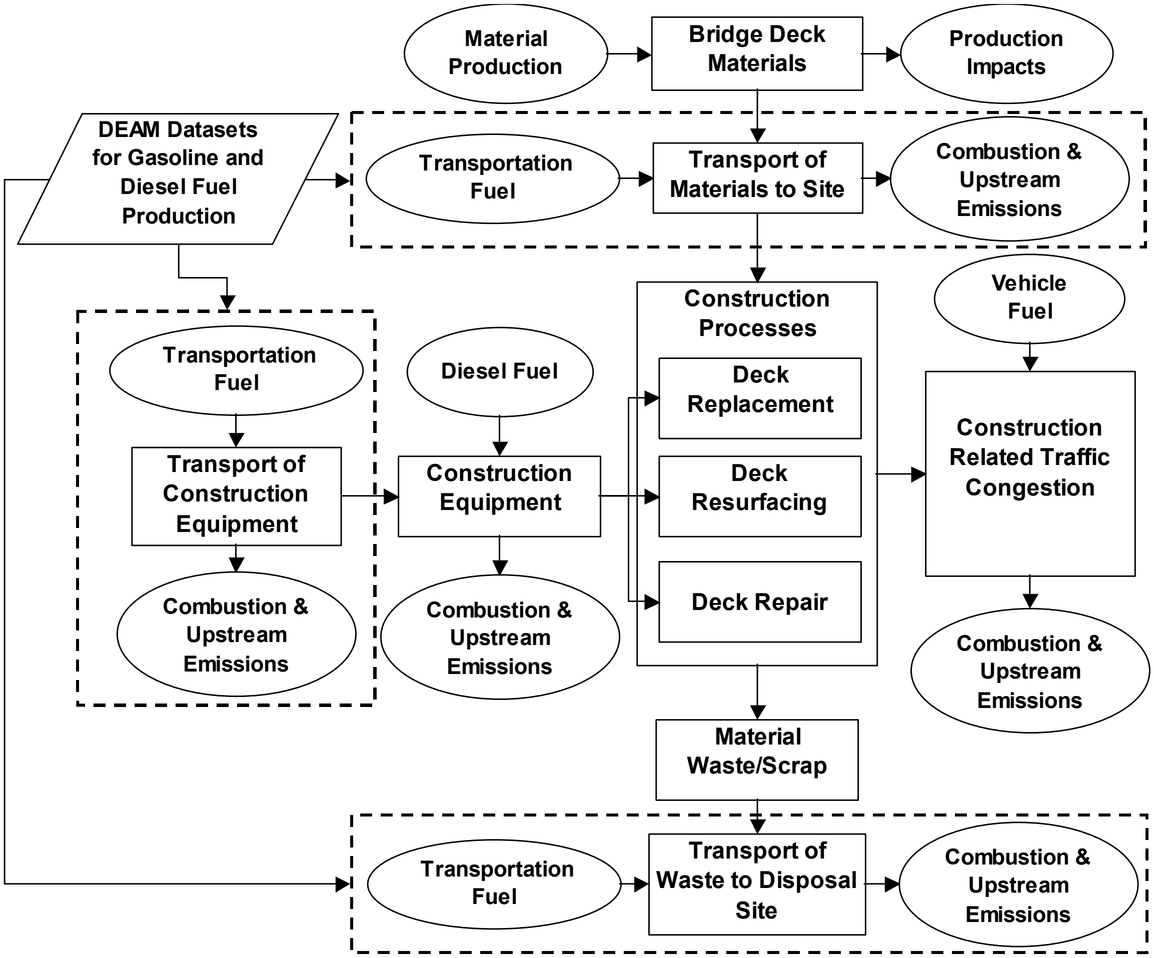


Figure 16. Life Cycle Model Boundary Diagram – Distribution Phase

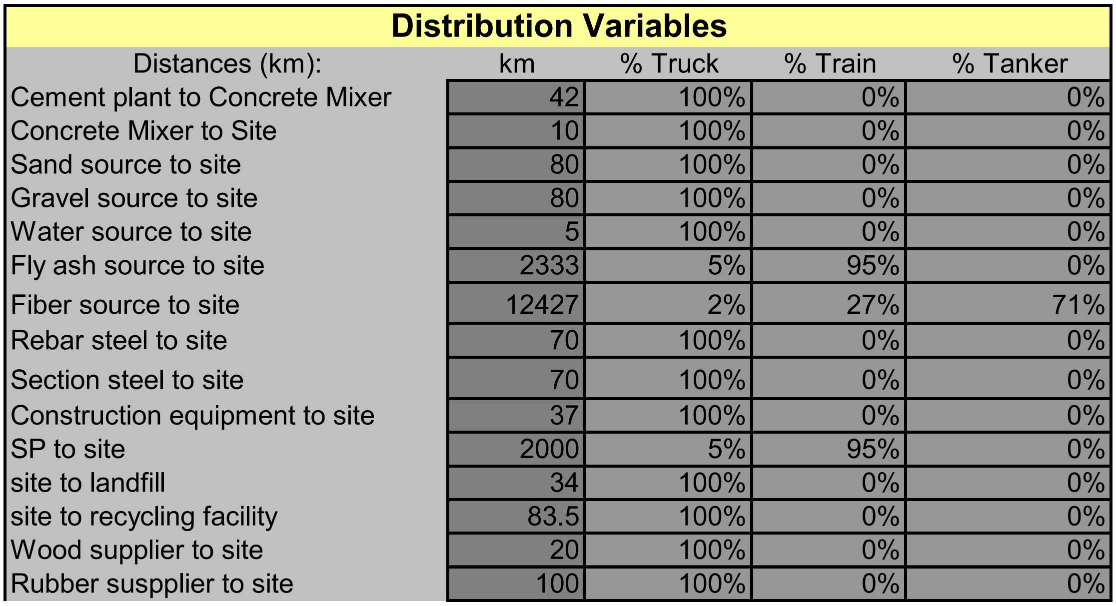
The volume of materials needed at each construction event assumes a certain scrap rate that is brought to the site and hauled away from the site without being incorporated into the volume of the bridge. Moreover, during deck resurfacing, joint or link slab replacement, and deck replacement the entire volume of the piece replaced is assumed to be removed. So in deck replacement for example, the entire deck is removed and hauled as waste, the volume of the deck plus a scrap rate is hauled to the construction site, and the scrap is then also hauled away as waste. Thus in this case everything brought to the site must have an equivalent quantity removed. The exception to this is patching and repair, where holes are filled but no volume of waste is expected to be removed. The distribution phase also accounts for the transport of construction equipment to the site. The machine weights are calculated in the *Construction* macro and transferred into the *Distribution* workbook.

4.4.1 *Materials and Distribution*

Materials may be transported by three modes, truck, rail and boat. All items must arrive at the construction site by truck, but some may begin their journey on sea tankers or rail. Figure 17 is a copy of an input table that was pulled directly from the LCA model. The table indicates the distances that materials are expected to travel to arrive to the construction site, and the modes of transportation used to get them there.

Materials and equipment must also be transported from the site. The “site to landfill” and “site to recycling facility” rows show the distance materials travel when they are removed from the construction site. All conventional concrete and ECC materials are assumed to go to landfill when they are removed for repair and reconstruction, or when they result as scrap from a construction event. While re-use of concrete waste is possible as a replacement for aggregate or crushed stone in applications such as road base (Kelly 1998), most concrete still ends up in a landfill. Rebar removed from the steel reinforced concrete, however, is assumed to go to recycling.

Appendix B contains sources for the distances shown in Figure 17.



Distribution Variables

Distances (km):	km	% Truck	% Train	% Tanker
Cement plant to Concrete Mixer	42	100%	0%	0%
Concrete Mixer to Site	10	100%	0%	0%
Sand source to site	80	100%	0%	0%
Gravel source to site	80	100%	0%	0%
Water source to site	5	100%	0%	0%
Fly ash source to site	2333	5%	95%	0%
Fiber source to site	12427	2%	27%	71%
Rebar steel to site	70	100%	0%	0%
Section steel to site	70	100%	0%	0%
Construction equipment to site	37	100%	0%	0%
SP to site	2000	5%	95%	0%
site to landfill	34	100%	0%	0%
site to recycling facility	83.5	100%	0%	0%
Wood supplier to site	20	100%	0%	0%
Rubber suspplier to site	100	100%	0%	0%

Figure 17. Input Table from LCA Model for Distribution Modes and Distances

4.5 End-of-Life

The end-of-life (EOL) module essentially creates a report based on the results of the other modules. Figure 18 shows in bold letters the life cycle module that calculates the values for that component, and then shows with background shading whether the component contributes to the EOL report.

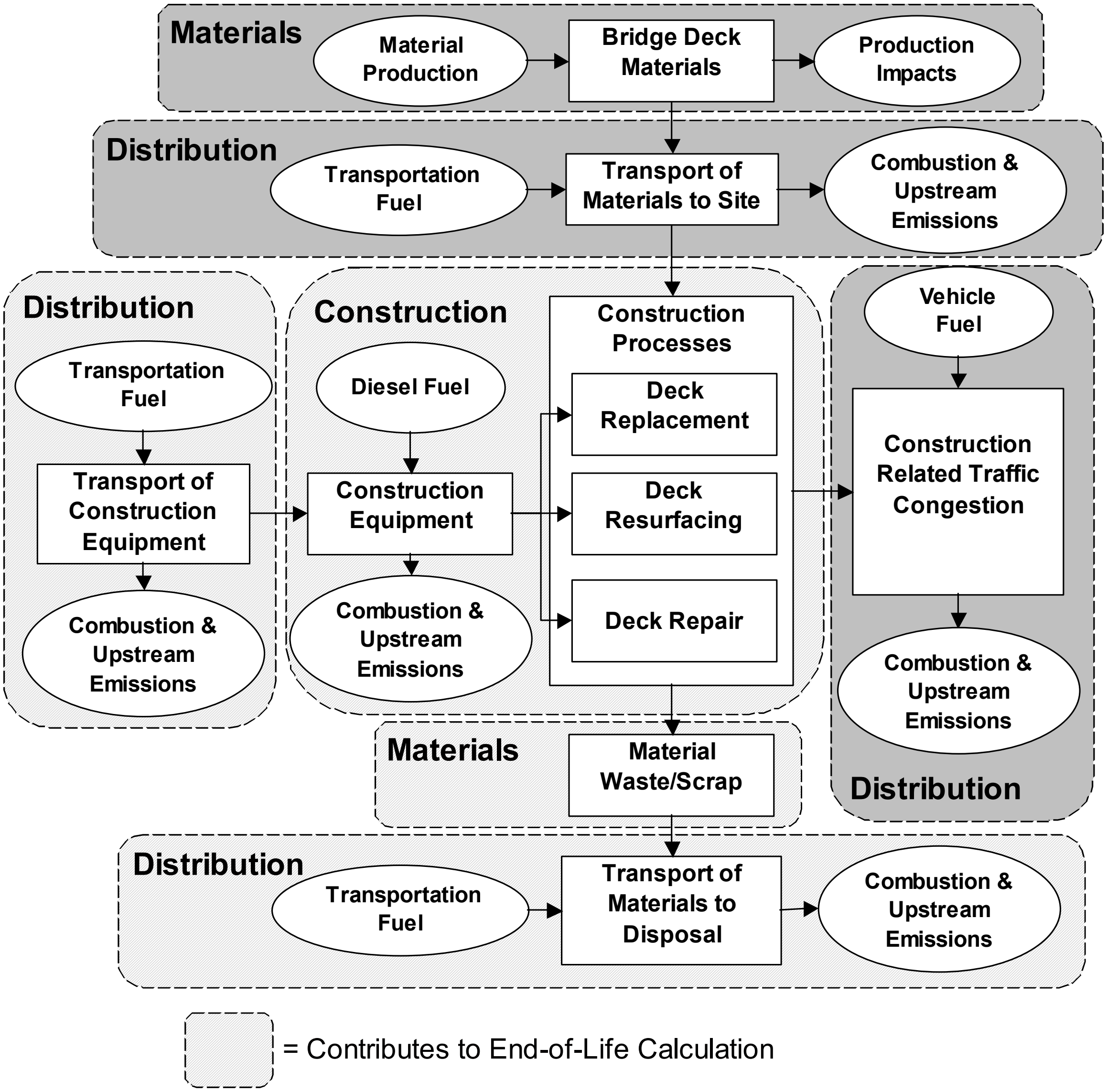


Figure 18. Life Cycle Model Boundary Diagram – End-of-Life Module

EOL accounts for the processes and materials that are part of the disassembly and disposal of the bridge deck system. The modules that contribute most significantly to the EOL inventory results are construction and distribution. For example, all construction processes are calculated in the construction module, but the results are allocated both to the construction and EOL phases in final reporting based on whether the process removes a part of the bridge deck or lays new materials in its place. Likewise, distribution is also split between distribution and EOL in final reporting. When materials are being hauled away from the construction site, the impacts are allocated to EOL rather than distribution.

There is one exception to the EOL reporting method. Construction related traffic always is reported in the traffic phase and is not ever allocated to the EOL phase – regardless of whether the construction process underway during the traffic congestion is allocated to EOL (i.e. bridge deck demolition and removal).

An important assumption in the EOL module is that the ECC and conventional systems have equal demolition processes. Because of ECC's durability and resistance to fracture, demolition could prove more difficult than for conventional concrete. ECC researchers are still evaluating whether alternative demolition processes will have to be planned for the material.

4.5.1 *Macro Logic Sequence for EOL*

The following steps outline the logic sequence for the EOL macros.

1. From *LCA_main* workbook verify which of the four possible SRC and ECC material formulations are to be analyzed in the run.
2. Evaluate transportation energy from *Distribution* that should be allocated to *EOL*. This portion includes energy and emissions for waste material transport away from the construction site to a disposal or recycling site and transport of construction equipment used in demolition processes.
3. Evaluate construction energy and emissions that should be allocated to *EOL* based on the specific construction subprocess. These include removal of slabs, deck materials, and joints; initial traffic control set-up; scarification; and hydro. The last two are methods of removing and cleaning the old deck or surface in preparation for laying a new one.
4. Summarize results from LCI data in *LCA_main* in *EOL*. This allocates the EOL portion of the total in the LCI between EOL and other phases.

5 Reference Data and Model Assumptions

5.1 Reference Data

The LCA model's starting point is the reference datasets for materials. These datasets provide the basic input values for all the results produced by the model output. Consistency in terms of what pollutants are produced and what inputs are required for a given material is important since they are aggregated in life cycle impact calculations. Moreover, datasets are likely to vary based on region or country. For example, the production impacts in the United States of producing cement are likely to be different than those in China or Europe, where production processes and environmental regulations are different.

The starting point for building a collection of datasets for this model began with Ecobilan's DEAM database. (Ecobilan 2001) Ecobilan is a French company that developed a life cycle analysis database tool that contains data for many materials and products. In some cases data are available for a single material from multiple world regions, other times the data are available only from a single region or country. While U.S. data is preferred it is not always available.

For many other constituents alternative sources were necessary. The Portland Cement Association (PCA) supplied life cycle data for cement (Nisbet et al. 2002). PCA is a cement industry organization that has begun addressing and measuring some of the impacts that the cement industry has on the environment. Data supplied by PCA was supplemented with DEAM data for a few categories that were not included in PCA data.

Data for the PVA fiber used in ECC was difficult to track down. Full life cycle data was not available for this material so a hybrid dataset created from data supplied by the material's producer and data from the Association of Plastic Manufacturers in Europe (APME) for polyethylene was used (Bousted 1999). The data fields supplied by the manufacturer were total primary energy consumption, carbon dioxide emissions, NOx emissions, SOx emissions, BOD (Biological Oxygen Demand) discharge, COD (Chemical Oxygen Demand) discharge, and waterborne suspended matter. All other data categories were substituted with polyethylene data from APME.

Superplasticizer data were likewise difficult to trace. Rather than data for this specific material, data for its precursor formaldehyde were used on an equal-weight basis. The use of formaldehyde data suggests that, while the LCA dataset should reasonably characterize superplasticizer, it is a conservative estimate of its total impacts.

Fly ash is considered to be a zero impact material in all categories except waste, where it has a negative value. Fly ash is a waste product of electricity production and other coal burning processes. Fly ash is diverted from the waste stream and displaces cement, thus earning the material a negative waste value. One gap in this data is that fly ash goes through some processing, such as grinding, before it can be used in cement, thus there should be some processing and transport energy included in the dataset. Some potential alternatives to cement and other concrete constituents that are waste products from industrial processes may be candidates for direct use, and these are being explored for use in new ECC formulations. Potential materials include industrial waste products such as green sand from forgery operations. These materials would have no additional processing energy associated with them. The suitability of these materials as direct substitutes for concrete constituents is still under evaluation by University of Michigan researchers at the Advanced Civil Engineering Materials Research Laboratory.

Appendix C provides the datasets used in the LCA model, and Appendix D provides the sources of the datasets. The datasets discussed above are the most complicated in so much as they come from compound sources or rely on data substituted from other materials.

The environmental assessment in this thesis focuses on the following impact categories; raw material consumptions, energy consumption, criteria air pollutants, criteria water pollutants, and greenhouse gas emissions. The air pollutants included in the assessment are methane, carbon monoxide, particulate matter (as PM_{10}), hydrocarbons, nitrogen oxides, and sulfur oxides. The water emissions included in the assessment are biological oxygen demand, ammonia, phosphate, oils, suspended matter, and dissolved matter. The greenhouse gas emissions used to calculate global warming potential, which is discussed in more detail in section 6.2.1, are CO_2, methane, and nitrous oxide. While many more pollutants were tracked that contribute to environmental impacts, these emissions were consistently reported throughout all data categories and thus can be considered the most reliable. The model is capable of tracking 169 different output categories, but not all datasets provide such comprehensive reporting.

5.2 Model Assumptions

The following table is a summary of model limitations, key life cycle model assumptions, and module assumption for the LCA computer model. All results, conclusions, and recommendations presented in this thesis should be considered in light of these assumptions and limitations.

Table 9. Model Limitations and Assumptions

Model Limitations	
Use of surrogate or incomplete data sets	
	Superplasticizer - formaldehyde, a precursor to superplasticizer, is used as surrogate data on a per-volume basis. This is likely an underestimate of life cycle burdens.
	Fly Ash - fly ash is only accounted for as a material diverted from waste stream; however fly ash goes through a grinding process prior to its substitution for cement and thus has some burdens that are unaccounted for.
	PVA fiber - polyethylene is used as surrogate data for the polyvinyl alcohol (PVA) material, and is combined with supplemental data from the manufacturer. A data set for PVA would be preferable.
Inability to resolve uneven service life intervals for alternative systems	
	The model is currently unable to resolve results for compared systems with unlike life cycle time frames. Improvements to the model should include an allocation process to allow differing time frames between systems. For more details see Section 3.2.

Key Life Cycle Model Assumptions	
A 60-year service life for both the ECC and conventional systems	
	This implies that the substructure has the same lifetime regardless of the design of the bridge deck.
ECC link slabs double the life of the concrete bridge deck	
	the deck and link slab replacement occur at year one.
Material production burdens constant over life cycle timeframe	
	Material production burdens are assumed to remain unchanged over the 60-year service life.

Module Assumptions for LCA Computer Model	
Traffic	The KyUCP traffic model is applied to estimate congestion resulting from construction activities. This model cannot account for detouring vehicles. Vehicle detouring is accounted for within the LCA model, and assumes that no congestion or back-up occurs on the roads that vehicles detour to.
Materials	As stated above in the model limitations, some materials have imperfect life cycle inventory data sets. Most notably, the PVA fiber, superplasticizer, and fly ash.
Construction	The construction phase assumes regular and predictable repair and reconstruction schedules, which may not always occur in real-world applications. Moreover, the construction equipment and construction processes are assumed to be unchanged over the 60 year-bridge life - with the exception of equipment emissions which are expected to improve.
Distribution	Distribution is based directly off of material weight and burdens are calculated in terms of weight and distance. The weight-distance burdens are assumed to remain constant over the 60-year bridge life.
End-of-Life	Demolition for ECC bridge deck system assumed to be equal to conventional system demolition.

6 Results

The goal of this LCA model is to assess the environmental life cycle burdens associated with two bridge deck design options, an ECC link slab design and conventional mechanical steel expansion joint design. The conclusions reached in this thesis are based on the relative performance of the two systems. Some key assumptions that affect the results include a 60-year bridge life for both systems at the beginning of the model run, as well as regular and periodic repairs at different intervals for both design options. Results from this model suggest that the ECC system is, in general, superior to the conventional system from an environmental LCA standpoint. This section provides model results for raw material consumption, energy consumption, air and water emissions, solid waste, and global warming potential.

6.1 Raw Material Consumption

Table 10 below shows the total primary energy used in material production from three standpoints, energy per kilogram, energy per deck replacement, and energy over the life cycle of the bridge deck. ECC is significantly more energy intensive per kilogram than conventional concrete. However, when the two bridge deck designs are compared, the difference between the two is somewhat muted. Most importantly, from a life cycle perspective the ECC system is far less energy intensive from a materials standpoint. This table shows the importance of long-term, holistic thinking with regard to infrastructure applications.

Table 10. Multi-Perspective Comparison of ECC and Conventional Concrete Material Energy

	Conventional System	ECC System	% More ECC
Total Primary Energy per kilogram of material (MJ)	3411.59	7103.04	51.97%
Total Primary Energy for Bridge Deck Replacement (MJ)*	6.31E+06	8.36E+06	32.45%
Total Primary Energy for Materials over 60-year bridge life (MJ)*	1.35E+07	7.47E+06	-44.64%

*Includes wood, an auxiliary construction material

Table 11 shows the raw material usage for six key materials in the two systems over the entire 60-year life cycle. Note that while Tables 3 and 4 showed greater cement content in the ECC formulation over SRC, because ECC is applied strategically and extends the life of the SRC deck, the ECC system uses considerably less limestone and other raw materials over the 60-year life cycle of the bridge.

Table 11. Life Cycle Raw Material Resource Use

Raw Material	Conventional System (metric tonnes)	ECC System (metric tonnes)	% Less ECC
Coal	124	67	54%
Limestone	757	406	54%
Natural Gas	140	84	60%
Oil	590	368	62%
Sand	852	443	52%
Water	24696	15351	62%

6.2 Energy Consumption

Figure 19 below shows the total primary energy consumed by each life cycle phase. The traffic phase dominates both the ECC and conventional system results, followed by the materials phase; these two dominant phases dwarf the construction, distribution, and EOL phases. In this and all subsequent figures "Δ traffic" is used to describe the traffic phase as a reminder that the traffic phase only shows the difference between impacts during construction related traffic congestion and impacts from normal traffic flow. The conventional system consumes 74874 gigajoules (GJ) in total primary energy and the ECC system consumes 44764 GJ in total primary energy, a 40% reduction from the conventional system.

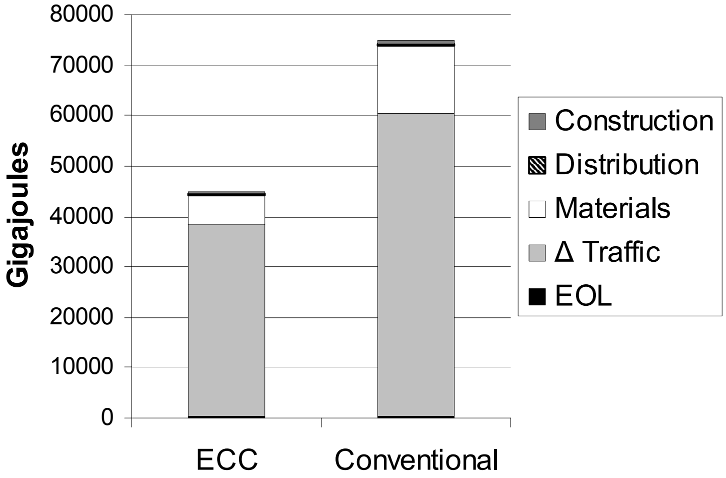


Figure 19. Total Primary Energy Consumption by Life Cycle Phase

Since energy consumption is dominated strongly by traffic related energy, further analysis of traffic energy was conducted. The model assumed that traffic levels stayed constant over the 60-year life of the bridge. The reason for this assumption was that congestion related traffic energy quickly dwarfed all other life cycle phases when a constant traffic growth rate was applied. Moreover, the real-world growth rate is unknown, and motorists tend to respond to constant congestion by reducing their average vehicle miles traveled. Thus, assumptions about long-term growth are difficult to make. In order to measure the impact of traffic growth rate scenarios the model was run using three annual growth rates, 0%, 1% and 2%. This analysis shows that the traffic congestion component of the model has the potential to overwhelm the life cycle energy of other elements in the model under traffic growth scenarios. Fig. 14 shows that at 2% growth, traffic related energy consumption grows to more than 13 and 23 times the 0% growth levels for the ECC and conventional systems, respectively. Considering that U.S. annual vehicle miles traveled is increasing by more than 2% per year on average (TransStats 2001), there is a potential for traffic related congestion to overwhelm all of the other elements in the LCA. In real world terms, however, motorists are likely to pursue alternate routes or modes of transport, and transportation agencies are likely to expand and build new roads under this traffic growth scenario, so such backups on a single roadway seem unlikely.

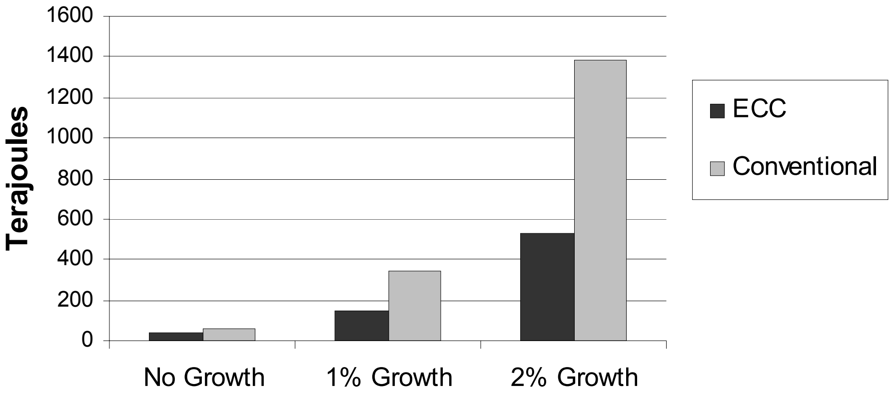


Figure 20. Sensitivity of Total Primary Δ Traffic Energy to Changes in Traffic Growth Rate

After traffic related energy consumption, material related energy consumption is most significant. Figure 9 in Section 4.1.2 showed that the cement content in conventional concrete and ECC dominates material energy. In Figure 9 and in the results described in this chapter, the wet kiln production process was assumed since it is what is regionally available. Table 5 showed that the kiln configuration used during cement production had the potential to reduce production energy. In support of this conclusion, Table 12 shows the total material life cycle production energy for the conventional and ECC bridge deck systems for the different kiln configurations available, as well as the national average for kiln types. Table 12 shows that if kiln technologies were updated, as much as a 10% improvement in the ECC system, and a 9% improvement in the conventional system are possible.

Table 12. Kiln Configurations and Total Life Cycle Material Production Energy

[Data provided by the Portland Cement Association **(Nisbet et al. 2002)**]

Kiln Type	Total Material Production Energy (TJ)		% Difference from Wet Process	
	Conv.	ECC	Conv	ECC
Wet Process	13.5	7.5	--	--
Long Dry Process	13.2	7.3	2.2%	2.5%
Dry Process with Pre-heater	12.5	6.9	7.5%	8.3%
Dry Process with Pre-heater and Pre-Calciner	12.3	6.7	9.2%	10.2%
Weighted US National Average	12.7	7.0	5.6%	6.2%

6.3 Select Air Pollutant Emissions

Other select air emissions in addition to CO_2 include nitrogen oxides (NO_X), sulfur oxides (SO_X), non-methane hydrocarbons (NMHC), particulate matter (PM_{10}), carbon monoxide (CO), and methane (CH_4). According to the USEPA, the following are impacts associated with the release of these pollutants (USEPA 2004):

1. NO_x is a general term for a group of reactive nitrogen and oxygen compounds that pose a hazard to human health, especially respiratory hazards from ground level ozone formation and the formation of nitrate particles. NO_x also poses a risk to and environmental health since it contributes to the formation of acid rain and plays a role in nutrification of water bodies.

2. SO_x emissions, compounds of sulfur and oxygen, also pose a risk to human and environmental health. SO_x is most well known in its form as SO_2, which contributes to the formation of acid rain, and can cause asthma and respiratory illnesses to worsen.

3. PM_{10} can also cause or exacerbate respiratory illnesses in humans, and can upset nutrient and pH balances where it falls since it may be transported great distances before falling to the surface of the earth. $PM_{2.5}$ is often a preferred measure for particulate matter and human health effects; however, most datasets only provide PM_{10} measures and thus this is the category reported in this thesis.

4. CO, which results from incomplete combustion, primarily impacts humans by causing central nervous system, respiratory or cardiovascular problems. At extremely high concentrations CO can even cause death.

5. CH_4 is primarily a concern because it is a powerful greenhouse gas, as discussed in section 6.2.1.

Figure 21 shows that the ECC system emits significantly less of each of these pollutants over the 60-year time horizon. The NO_x emissions warrant an explanation since the results are not intuitive. This pollutant shows *negative* values for the traffic phases for both ECC and conventional systems; moreover, the ECC system unexpectedly shows more negative results than the conventional system. This is because NO_x is produced in greater quantities at high speeds than at low speeds. So while most pollutants are increased by congestion, NO_x is an exception to the rule. When the baseline emissions are subtracted from the construction phase traffic emissions, the consequence is a negative value for NO_x emissions. The reason the ECC shows more negative results than the conventional system is due to the timing of construction events over the 60-year service life. For NO_x emissions there is a benefit associated with construction events only in the short term because of expected reductions in NO_x emissions at high speeds in the future. For the ECC bridge deck system, deck replacement occurs only at year one. This construction event is estimated to take a total of 68 days, 18 days longer than a conventional deck replacement takes. Additionally, the 68 days comprise 55% of the total number of construction days in the ECC system's life cycle, meaning that the construction activities for the ECC life cycle are weighted heavily towards the first year. Because of this weighting of construction days early in the ECC system timeline, the results for ECC show more negative NO_x values than the conventional system.

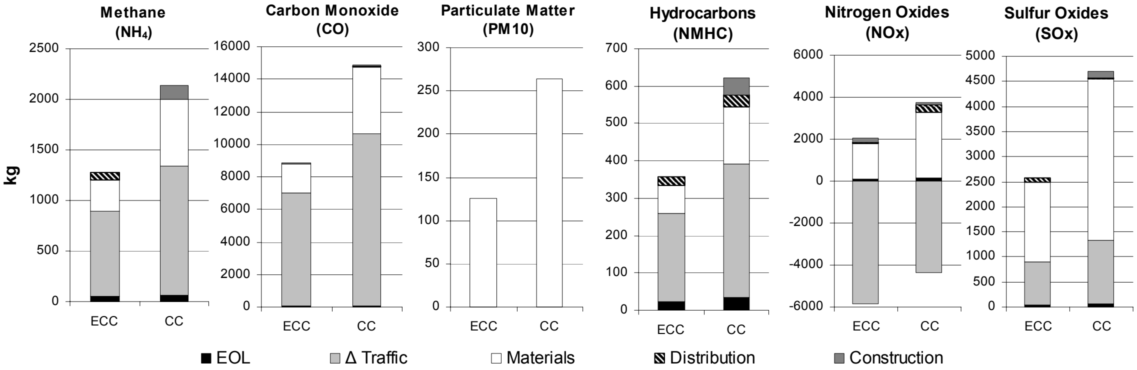


Figure 21. Air Emissions by Life Cycle Phase

6.4 Water Pollutant Discharges

Emissions to water from each life cycle phase are shown in Figure 22 for biological oxygen demand (BOD), ammonia, phosphate, oils, suspended matter, and dissolved matter.

1. BOD is a measurement of how fast microorganisms in the water use dissolved oxygen (DO) in the water to consume dissolved organic compounds in the water.

2. Ammonia is a chemical pollutant that is harmful to aquatic life.

3. Phosphate is a form of non-organic nutrient pollution. When introduced to bodies of water, phosphate can cause rapid algaeic blooms and plant growth. When the blooms and plants die they fall to the bottom and deplete DO levels as microorganisms consume them.

4. Oils, like other biodegradable wastes, cause a similar process of DO depletion as described above for the algaeic blooms resulting from phosphate pollution.

5. Suspended matter can impact waterways by causing rapid sedimentation as it falls out of its suspended state.

6. Dissolved matter can impact water by affecting water chemistry, such as changing the level of acidity.

The ECC system results in a 34% to 76% reduction of water pollutants. The large amounts of suspended matter, oils, and biological oxygen demand from the traffic phase are a result of the fuel production processes.

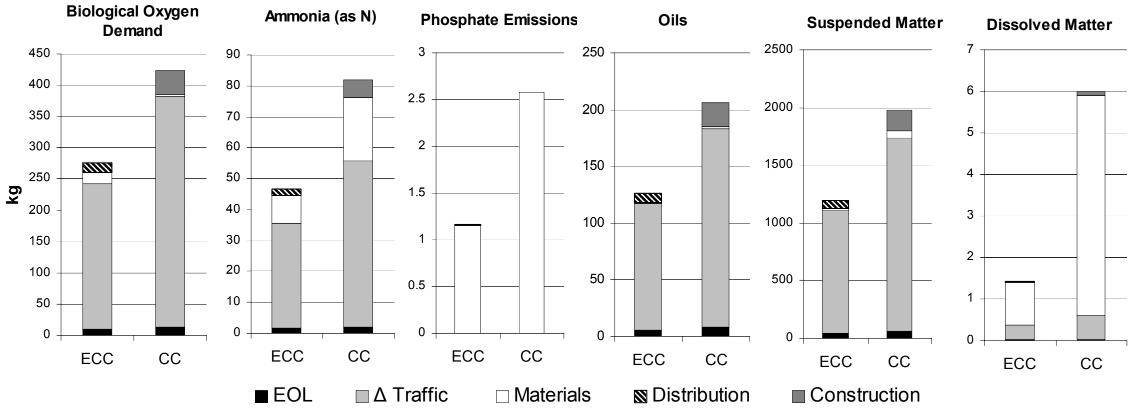


Figure 22. Water Emissions by Life Cycle Phase

6.5 Solid Waste Production

Life cycle solid waste generation totaled 3970 metric tonnes for the conventional system, and 2000 metric tonnes for the ECC system, approximately half the solid waste generation of the conventional system. In both systems, bridge materials constitute the majority of solid waste, accounting for 87% in the ECC system and 90% in the conventional system. This suggests that improvements still need to be made in the re-usability or recyclability of concrete and its components.

6.6 Greenhouse Gas Emissions

The results of greenhouse gas (GHG) emissions are similar to those for energy consumption. Traffic related carbon dioxide (CO_2) dominates total GHG emissions for both the ECC and conventional bridge systems. Material production is the only other significant contributor. Figure 23 shows the total greenhouse gas emissions in metric tonnes of CO_2 equivalent for each system. This is calculated by multiplying the mass of each GHG emission by its global warming potential (GWP). The GWP's are based on the radiative forcing (heat absorbing ability) of each GHG as well as the decay rate of each gas relative to carbon dioxide over a 100-year time horizon. The GHG emissions included in this analysis are CO_2 (GWP = 1), methane (GWP = 23), and nitrous oxide (GWP = 296) (Houghton 2001). Despite the contribution to global warming of the two other gases, CO_2 overwhelmingly dominates GWP results. In the ECC system CO_2 represents 98% of total life cycle GWP, and in the conventional system CO_2 represents 99% of total life cycle GWP. The ECC system shows a reduction of 33% in GWP over the conventional system. Typically, CO_2 emissions mirror energy consumption; however, the production of cement involves the release of additional CO_2 during pyroprocessing (conversion of calcium carbonate to calcium oxide), which results in twice the CO_2 that would be produced from energy consumption alone (CEMBUREAU 1998). This additional contribution of CO_2 from cement production is evident in the comparison of Figures 19 and 23 wherein material production represents a greater portion of the total CO_2 emissions than it does total energy consumption.

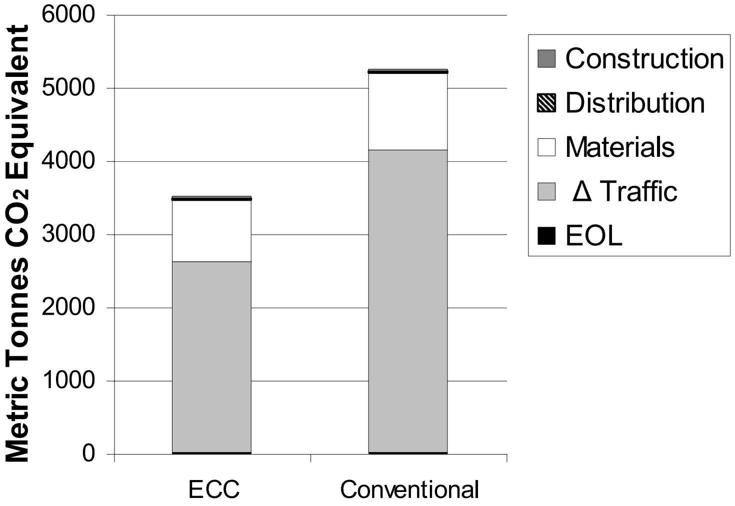


Figure 23. Global Warming Potential Reported in Metric Tonnes of CO_2 Equivalent

7 Conclusions and Recommendations for Future Research

7.1 Conclusions

This thesis defines a framework and computer modeling approach for the life cycle assessment of alternative concrete bridge deck designs. The following conclusions address key features of the model, and results and conclusions from the application of the model to two bridge deck design alternatives; an ECC link slab design and a conventional mechanical steel expansion joint design. Results should be considered in light of the assumptions and limitations of the model as outlined in Table 9.

1. An expanded scope over previous LCA studies.

This model broadens the scope of bridge LCA studies by accounting for the dynamic nature of the interlinked bridge and traffic systems. The traffic system proved to be the most significant contributor to many categories in the LCA results; thus, this new scope is an important development in LCA applications to bridges and similar infrastructure systems.

2. LCA model flexibility.

With over 100 flexible parameters programmed in the LCA computer model, users can explore the impacts of changes in material formulation and properties as well as test the sensitivity of the model with regard to key assumptions. Testing the impacts of material choice on long-term applications is a key feature in improving infrastructure sustainability. Moreover, sensitivity analysis allows for improved assessment of the reliability of model results.

3. The ECC link slab system resulted in significantly lower environmental impacts.

Over a 60-year service life, the ECC system resulted in a savings of more than 50% in materials and energy compared to the conventional system. This results primarily from the reduced number of repair and reconstruction events modeled for the ECC system.

4. Construction related traffic proved to be a key determinant of environmental impact.

A key finding from life cycle modeling was the importance of construction related traffic on the environmental performance of both deck systems. In the baseline scenario of 0% traffic growth over the 60-year service life of the bridge, construction related traffic energy comprised 80% of total primary life cycle energy for the conventional system and 85% of total primary life cycle energy in the ECC system. Traffic related air emissions also dominate results for carbon monoxide, methane, hydrocarbons, and greenhouse gas emissions in the form of carbon dioxide.

Figure 20 showed that when traffic growth was varied between 0 and 2%, changes in the amount of total primary energy consumed by the phase increased by 130% and 230% for the ECC and conventional systems, respectively. Because of the significant impact that traffic has on the LCA results, assessing long term traffic growth patterns and accurately predicting maintenance and repair schedules for a system is critical to evaluating the performance of alternative materials.

In order to address some of the uncertainty in traffic modeling, a sensitivity analysis was performed in Section 4.4.3. The analysis showed that the volume of vehicle traffic that detoured had more impact on energy consumption than the length of the detour. This suggests that improved traffic management and planning during construction events could reduce the impact of construction related traffic, as long as significant congestion does not occur on detour routes.

5. Strategic application of ECC material results in improved environmental performance.

This model showed that, while ECC is more energy intensive on a per mass basis, its strategic application in a bridge deck as link slabs reduces overall material energy consumption, raw material consumption, air pollution, water pollution, greenhouse gas emissions, and total primary energy consumption over the life cycle of the bridge deck.

6. Improvements in the sustainability of infrastructure will require improved material selection criteria.

The significant improvements of the ECC system over the conventional system forecasted by this model show the need for updated policy and removal of institutional barriers to allow for novel materials and designs to be incorporated in road construction. Improving durability of road systems is especially important because of the diverse nature of impacts, and the long-lived nature and consequences of infrastructure systems.

7. This model can facilitate additional research of ECC or other novel material applications in infrastructure systems.

Lessons-learned from this modeling, like understanding the difficulty of determining how to approach life cycle timeframes of different systems, will make future modeling more streamlined.

7.2 Future Research

An exploration of the deficiencies of this model framework, as well as integration of the other elements of sustainability, namely economic and social impacts, would yield a more holistic measure of the benefits of one bridge system over another. The following are suggestions for future research themes:

1. Fully integrate the LCA model with a life cycle cost (LCC) model.

A fully integrated LCC model would serve as a tool for evaluating the bridge deck infrastructure from a holistic sustainability perspective – integrating environmental, social and economic indicators. Such a model could enhance infrastructure sustainability and investment decisions (Norris 2001).

LCA and LCC models have previously been integrated for several other product systems including automotive parts (Keoleian and Kar 2003) and photovoltaics (Keoleian and Lewis 2003). The LCA model is essential to measure the magnitude of the pollution externalities that can be monetized using unit damage costs from environmental economics. The infrastructure system investigated in this study, however, represents a greater modeling challenge given its complexity in terms of the continual material and capital investments over a long service life.

2. Model additional concrete infrastructure systems such as roadways and concrete pipe.

While the LCA computer model is tailored to this specific bridge deck application, its dynamic nature and the larger integrated framework of macro-scale modeling and microscale tailoring can be applied to other infrastructure systems such as roadways and concrete pipe.

3. Consider changes over time in material production energy intensities and emissions factors in future modeling.

The impacts of material production and distribution may change over time. Future model refinements should include adding modeling capability to vary material production burdens over time.

4. Expand the scope of the LCA model to include other advanced materials.

ECC is only one of many other advanced materials that can be applied to improve the life cycle performance of bridge decks and other concrete infrastructure systems. Additional research and modeling can be pursued for other advanced materials, as well as additional ECC formulations with enhanced performance from mechanical and environmental standpoints.

5. The effect of ECC link slabs on bridge deck life warrants further investigation.

This analysis was predicated on the assumption that the ECC link slab would double the life expectancy of the bridge deck relative to the conventional steel joint. Different assumptions about the effect of ECC link slabs on bridge deck life are expected to change the results of this model significantly. This highlights the need for continued testing of ECC and other new materials to accurately model their long-term impacts.

6. Continue and expand current testing of ECC performance and durability.

While researchers have completed countless laboratory tests and initiated one on-site application of an ECC link slab, many questions still remain with regard to the ECC system's effectiveness in extending the life of the concrete bridge deck. Continued laboratory testing as well as real-world site testing is necessary to confirm or challenge the assumptions about durability and repair of the ECC link slab system.

Appendix A: Material Usage in Each Construction Event Type

Conventional - Deck Replacement

material	*mass (kg)*	*process mass (kg)*
Concrete (Total)	1142635.4	1159774.913
Constituent Materials		
Cement	238905.35	242488.9267
Gravel	472770.5	479862.0533
Sand	330132.92	335084.9093
Water	100803.94	102316.0028
Rebar steel	30626.304	31238.83008
Section steel	376800	376800
Water (additional)	10000	10000
Wood	28866.214	28866.2136
Epoxy	22.447859	22.44785876

ECC - Bridge Deck Replacement

material	*mass (kg)*	*process mass (kg)*
ECC (Total)	169455.77	171997.6112
Concrete (Total)	857886.08	825588.534
Constituent Materials		
Cement	274489.71	278607.0583
fly ash	57485.666	58347.95081
PVA fiber	2092.1472	2123.529408
sand	352057.41	357338.2724
super-plasticizer	1408.176	1429.29864
water	101227.74	102746.1537
Gravel	450353.46	367729.9541
Rebar steel	30626.304	31085.69856
Section steel	376800	376800
Water (additional)	1000	1000
Wood	29585.464	29585.46402
Epoxy	22.447859	22.78457665

Conventional - Deck Resurfacing

material	*mass (kg)*	*process mass (kg)*
Concrete (Total)	267006.12	271011.2098
All Constituent Materials		
Cement	55826.373	56663.76868
Gravel	110474.97	112132.0992
Sand	77144.039	78301.19933
Water	23555.432	23908.76316
Rebar steel	236.87532	241.6128264
Water (additional)	6000	6000
Wood	358.23606	358.23606
Epoxy	0.1736202	0.173620158
Rubber	88.128	88.128

ECC - Bridge Deck Resurfacing

material	*mass (kg)*	*process mass (kg)*
Concrete (Total)	212826.56	216018.9557
Constituent Materials		
Cement	44498.362	45165.83702
Gravel	88057.939	89378.80829
Sand	61490.352	62412.70728
Water	18775.68	19057.3152
Water (additional)	5000	5000
Wood	128.44272	128.44272

ECC - Bridge Deck Repair

material	*mass (kg)*	*process mass (kg)*
Concrete (Total)	5667.6125	5752.626688
Constituent Materials		
Cement	1185	1202.775
Gravel	2345	2380.175
Sand	1637.5	1662.0625
Water	500	507.5

ECC - Bridge Deck Repair

material	*mass (kg)*	*process mass (kg)*
Concrete (Total)	5667.6125	5752.626688
Constituent Materials		
Cement	1185	1202.775
Gravel	2345	2380.175
Sand	1637.5	1662.0625
Water	500	507.5

Appendix B: Distance Calculations Data Sources

Unless otherwise specified, these and all other construction materials are based on the distance between local suppliers and the selected bridge site. The Mapquest® online service was used to calculate truck distances if not available from the supplier (Mapquest 1996 - 2003).

1. PVA fiber transportation modeled as Tokyo to LA via tanker based on location of supplier (http://www.angelfire.com/md2/timewarp/cursortrail.html) and LA to Ann Arbor via truck.
2. Cement from the Holcim Cement Company's Dundee Plant located in Dundee, Michigan.
3. Fly ash distance is based on a supplier located in San Antonio, Texas.
4. The landfill selected for disposal is the Onyx – Arbor Hills landfill in Northville, Michigan.
5. The steel recycling facility, Global Alloys, is located in Troy Michigan.
6. Construction equipment is transported from a local construction equipment rental company, United Rentals, in Taylor, MI.
7. Killins Concrete in Ann Arbor, MI has a concrete mixing plant and supplies sand and gravel.

Appendix C: Life Cycle Inventory Reference Datasets

Appendix C: Fly Ash through Superplasticizer

per unit	Fly Ash	Coal Production (under-ground mined)	Coal Combus-tion (US mix)	Sand	Gravel	Diesel fuel production	Gasoline production	Rebar Steel	EAF steel (section)	Electricity (US grid)	PVA fiber	Super-Plastcizer (as Formaldehyde)
1 Barium Sulfate (BaSO4, in ground)	kg	MJ	kg	kg	kg	kg	kg	kg	MJ	kg	kg	1 kg-km
1 Bauxite (Al2O3, ore)				0	0						0	0
1 Calcium Sulfate (CaSO4, ore)		5.16E-08		8.041E-08	8.041E-08	0.0001074	2.30E-04			2.212E-07	0.0003	0
1 Clay (in ground)				0	0						0	0
1 Coal (in ground)				0	0						0.00002	0
1 Diesel fuel		1.01581	0.1365747	0.0030043	0.0030043	0.0362456	0.048802	0.0291671	0.048937	0.0942445	0.0898693	0.244714
1 Dolomite (in ground)				0	0						0.00E+00	0.00E+00
1 E Feedstock Energy				0	0			0.0001819	0.0105666		0.00E+00	0.00E+00
1 E Fuel Energy		29.3401	-3.98501	0	0	44.37	45.901	0.126673	-0.219137	2.54E-01	61.34	11.6036
1 E Non Renewable Energy		0.716309	4.0384	0.0354	0.0354	7.43795	11.9273	8.28332	9.73292	3.77E+00	18.11	23.5639
1 E Renewable Energy		30.0215		0	0	7.3885	11.8606	6.11824	7.22213	3.90E+00	78.99	35.1342
1 E Total Primary Energy		0.0200566		0	0	0.0489663	0.0658947	2.03658	1.91223	1.27E-01	0.46	0.0333654
1 Electricity		30.0564	0.0533869	0.067015	0.067015	7.438	11.9273	8.40989	9.50192	4.03E+00	101	35.1675
1 Ferrous Scrap				0.031615	0.031615					9.80E-03	2.58	0.264928
1 Gypsum				0	0			1.1289021	1.1177213		0.00E+00	0.00E+00
1 Iron (Fe, ore)				0	0						0.00E+00	0.00E+00
1 lignite				0	0			-0.014308	-0.031379		0.0002	0
1 Limestone (CaCO3, in ground)				0	0						0.00E+00	0.00E+00
1 Natural Gas (in ground)		0.0011675	0.0211206	0.0002371	0.0002371	0.0028735	0.0038783	0.0286321	0.0781434	0.0074379	0.00015	0.0033808
1 Oil (in ground)		0.0007727	0.0006527	0.0002302	0.0002302	0.117135	0.188909	0.0690544	0.0605479	0.0047492	0.833857	0.478843
1 Raw Materials (unspecified)		0.0030917	8.29E-05	0.0008401	0.0008401	1.06489	1.08119	4.69E-02	0.0241601	0.0035578	0.796222	0.104767
1 Sand (in ground)				0	0						0	0
1 Sodium Chloride (NaCl, in ground or in sea)		3.16E-08		4.928E-08	4.928E-08	6.58E-05	1.41E-04			1.355E-07	0.00E+00	0
1 Sulfur (S, in ground)		1.45E-08		2.261E-08	2.261E-08	3.02E-05	6.48E-05			6.219E-08	7.00E-03	0.00E+00
1 shale				0	0						0.00E+00	0.00E+00
1 Uranium (U, ore)				0	0						0.00E+00	0.00E+00
1 Water Used (total)		2.49E-07	9.17E-09	5.058E-08	5.058E-08	6.10E-07	8.21E-07			1.587E-06	0.00E+00	4.16E-07
1 Zinc (Zn)		0.0130042	0.0019478	0.0189666	0.0189666	25.2244	53.9136	4.13307	1.05942	0.0547514	18	0.0161601
2 Non-Allocted by products				0	0			-0.003678	-0.006955		0.00E+00	0.00E+00
2 Recovered Matter (total)				0	0			0.0144609	0.0245395		0	0
2 Recovered Matter: Aluminum Scrap		0.0007458		0.0001515	0.0001515	0.0018264	0.0024594			0.0047511	0	0
2 Recovered Matter: Ash		2.10E-10		3.271E-10	3.271E-10	4.37E-07	9.37E-07			8.998E-10	0.00E+00	0.00E+00
2 Waste (hazardous)		0.0007458		0.0001515	0.0001515	0.0018259	0.0024585			0.0047511	0	0
2 Waste (municipal and industrial)		7.08E-07		1.105E-06	1.105E-06	0.0014762	3.16E-03			3.039E-06	0.00007	0.000205
2 Waste (total)		1.15E-06		1.799E-06	1.799E-06	0.002404	5.14E-03			4.957E-06	0.0031	0
2 Waste (unspecified)	-1	0.397933	0.0344343	0.015804	0.015804	0.194374	0.264742	0.0061403	0.0653055	0.495688	0.03417	0.057389
2 Waste (unspecified, to incineration)		0.3238	0.0344343	0.0007466	0.0007466	0.0090098	0.0121297			0.0234201	0	0.057184
2 Waste: Bauxite Residues (red mud)		2.41E-08		2.914E-08	2.914E-08	3.73E-05	3.78E-05			1.161E-07	0.00E+00	0.00E+00
2 Waste: FGD Sludge		1.40E-08		2.182E-08	2.182E-08	2.92E-05	6.25E-05			6.002E-08	0.00E+00	0.00E+00
2 Waste: Mineral (inert)		0.0002342	0.0048585	4.756E-05	4.756E-05	0.0005631	0.0007696			0.0014923	0	0
2 Waste: Non Toxic Chemicals (unspecified)		3.00E-09		4.683E-09	4.683E-09	6.26E-06	1.34E-05			1.288E-08	2.20E-02	0.00E+00
2 Waste: Slags and Ash (unspecified)		7.04E-10		1.097E-09	1.097E-09	1.47E-06	3.14E-06			3.019E-09	2.00E-03	0.00E+00
2 Waste: mining + tailing	-1	0.0725833		0.0147402	0.0147402	0.177624	0.239091			0.462402	0.007	0
3 (ar) Radioactive Substance (unspecified)				0	0						0	0
3 Acenaphthene (C12H10)		1.06E-06		1.65E-06	1.65E-06	0.0022054	4.73E-03			4.54E-06	0	0
3 Acenaphthylene (C12H8)		3.77E-09		1.089E-07	1.089E-07	1.37E-08	2.15E-08			2.401E-08	0.00E+00	0.00E+00
3 Acetaldehyde (CH3CHO)		1.85E-09		1.228E-06	1.228E-06	5.71E-09	8.16E-09			1.177E-08	0.00E+00	0.00E+00
3 Acetophenone (C8H8O)		4.21E-06		4.394E-05	4.394E-05	1.03E-05	1.39E-05			2.68E-05	0.00E+00	2.55E-06
3 Acrolein (CH2CHCHO)		1.11E-07		2.248E-08	2.248E-08	2.71E-07	3.65E-07			7.052E-07	0.00E+00	5.27E-08
3 Aldehyde (unspecified)		2.14E-06		5.671E-06	5.671E-06	5.24E-06	7.06E-06			1.363E-05	0.00E+00	2.08E-08
3 Aluminum (Al)		0.0013194	6.91E-05	0.0002502	0.0002502	0.0038181	0.006596			0.0048269	0.005	0.0042026
3 Ammonia (NH3)		3.58E-08		4.336E-08	4.336E-08	5.55E-05	5.63E-05			1.727E-07	0.00E+00	7.23E-08
3 Anthracene (C14H10)		0.0001476	1.74E-06	2.456E-05	2.456E-05	0.0055247	0.0098402			0.0006574	0	0.0183566
3 Antimony (Sb)		1.55E-09		2.301E-07	2.301E-07	5.53E-09	8.17E-09			9.901E-09	0.00E+00	2.79E-08
3 Aromatic Hydrocarbons (unspecified)		3.15E-07	1.10E-06	6.45E-08	6.45E-08	1.60E-06	2.81E-06			2.006E-06	0.00E+00	5.08E-05
3 Arsenic (As)		6.09E-11		9.497E-11	9.497E-11	1.27E-07	2.72E-07			2.612E-10	0.00E+00	0.00E+00
3 Barium (Ba)		1.30E-05	9.79E-05	2.648E-06	2.648E-06	3.77E-05	4.92E-05			8.285E-05	0.00E+00	2.91E-05
3 Benzene (C6H6)		1.23E-07		2.528E-08	2.528E-08	8.34E-07	1.49E-06			7.816E-07	0.00E+00	3.34E-05
3 Benzo(a)anthracene		0.000273		9.465E-05	9.465E-05	0.0367077	0.0633323			0.0017038	0	0.177624
3 Benzo(a)pyrene (C20H12)		5.94E-10		6.094E-08	6.094E-08	3.23E-09	5.29E-09			3.784E-09	0.00E+00	0.00E+00
3 Benzo(b)fluoranthene		2.83E-10		5.637E-08	5.637E-08	1.82E-09	2.62E-09			1.801E-09	0.00E+00	0.00E+00
3 Benzo(bjk)fluoranthene		3.50E-12		9.912E-08	9.912E-08	1.27E-09	2.24E-09			2.104E-11	0.00E+00	0.00E+00
3 Benzo(ghi)perylene		8.12E-10		1.648E-10	1.648E-10	1.99E-09	2.68E-09			5.171E-09	0.00E+00	0.00E+00
3 Benzo(k)fluoranthene		2.02E-10		6.762E-08	6.762E-08	1.44E-09	2.36E-09			1.284E-09	0.00E+00	0.00E+00
3 Benzyl Chloride (C7H7Cl)		3.50E-12		9.912E-08	9.912E-08	1.27E-09	2.24E-09			2.104E-11	0.00E+00	0.00E+00
3 Beryllium (Be)		5.17E-06		1.049E-06	1.049E-06	1.27E-05	1.70E-05			3.291E-05	0.00E+00	2.73E-08
3 Bromoform (CHBr3)		1.49E-06		3.026E-07	3.026E-07	3.79E-06	5.15E-06			9.49E-06	0.00E+00	1.85E-11
3 Butane (C4H10)		2.88E-07		5.845E-08	5.845E-08	7.05E-07	9.49E-07			1.833E-06	0.00E+00	8.57E-14
3 Cadmium (Cd)		3.99E-06		1.681E-06	1.681E-06	0.0013444	2.32E-03			2.41E-05	0	0

Appendix C. Fly Ash through Superplasticizer

per unit	Fly Ash	Coal Production (under-ground mined)	Coal Combus-tion (US mix)	Sand	Gravel	Diesel fuel production	Gasoline production	Rebar Steel	EAF steel (section)	Electricity (US grid)	PVA fiber	Super-Plastcizer (as Formaldehyde)
3 Propane (C3H8)		6.77E-14		1.055E-13	1.055E-13	1.41E-10	3.02E-10			2.902E-13	0.00E+00	5.91E-08
3 Propionaldehyde (CH3CH2CHO)		1.80E-06		3.654E-07	3.654E-07	4.50E-06	6.10E-06			1.146E-05	0.00E+00	0.00E+00
3 Pyrene (C16H10)		2.80E-06		2.727E-05	2.727E-05	6.87E-06	9.25E-06			1.786E-05	0.00E+00	2.30E-07
3 Selenium (Se)		2.44E-09		8.723E-07	8.723E-07	9.50E-09	1.43E-08			1.557E-08	0.00E+00	0.00E+00
3 Silicon (Si)		9.62E-06		1.954E-06	1.954E-06	2.53E-05	3.36E-05			6.127E-05	0.00E+00	6.25E-11
3 Sodium (Na)		3.10E-08		3.757E-08	3.757E-08	4.81E-05	4.88E-05			1.497E-07	0.00E+00	0.00E+00
3 Styrene (C6H5CHCH2)		1.84E-07		2.226E-07	2.226E-07	0.0002847	2.89E-04			8.866E-07	0	0
3 Sulfur Oxides (SOx as SO2)		1.84E-07		3.037E-06	3.037E-06	4.52E-07	6.09E-07			1.175E-06	0.00E+00	6.89E-06
3 Tetrachloroethylene (C2Cl4)		0.159748	2.22885	0.0372285	0.0372285	2.09494	3.23704	2.04923	0.707584	0.890977	14	4.9722
3 Toluene (C6H5CH3)		3.17E-07		6.444E-08	6.444E-08	7.77E-07	1.05E-06			2.021E-06	0.00E+00	3.69E-07
3 Trichloroethane (1,1,1-CH3CCl3)		2.24E-06		5.028E-06	5.028E-06	9.74E-06	1.51E-05			1.425E-05	0.00E+00	7.47E-05
3 Vanadium (V)		1.48E-07		2.997E-08	2.997E-08	3.61E-07	4.87E-07			9.402E-07	0.00E+00	0.00E+00
3 Vinyl Acetate (C4H6O2)		1.58E-06		8.069E-07	8.069E-07	0.0007486	7.68E-04			9.343E-06	0	0.0003163
3 VOC (g)		5.61E-08		1.139E-08	1.139E-08	1.37E-07	1.85E-07			3.573E-07	0.00E+00	3.03E-06
3 Xylene (C6H4(CH3)2)				0	0			0.0986055	0.159111		0	0.0011893
3 Zinc (Zn)		2.91E-07	2.23E-06	6.917E-06	6.917E-06	2.67E-06	4.37E-06			1.853E-06	0.00E+00	8.02E-06
4 Acids (H+)		1.06E-06		2.311E-07	2.311E-07	2.57E-05	4.52E-05	1.88E-02	0.0166622	6.756E-06	0.00E+00	2.81E-04
4 Aluminum (Al3+)		1.72E-09		5.031E-10	5.031E-10	2.39E-07	4.13E-07			1.075E-08	7.00E-02	0.00E+00
4 Ammonia (NH4+, NH3, as N)		1.64E-07		2.561E-07	2.561E-07	0.0003422	7.33E-04			7.044E-07	0	2.868E-10
4 AOX (Adsorbable Organic Halogens)		4.48E-05		5.162E-05	5.162E-05	0.0653616	1.42E-01	3.61E-02	0.0238396	0.00022	0.005	0.0056831
4 Aromatic Hydrocarbons (unspecified)		4.33E-13		6.753E-13	6.753E-13	9.02E-10	1.93E-09			1.858E-12	0.00E+00	0.00E+00
4 Barium (Ba++)		1.01E-10		1.583E-10	1.583E-10	2.11E-07	4.53E-07			4.354E-10	0.00E+00	0.00E+00
4 BOD (g)		3.25E-10		5.065E-10	5.065E-10	6.77E-07	1.45E-06			1.393E-09	0.00E+00	6.56E-09
4 Cadmium (Cd++)		0.0002307	1.26E-05	0.0003391	0.0003391	0.453115	0.97122			0.0009343	8	0.0625466
4 Chlorides (Cl-)		3.38E-13		5.276E-13	5.276E-13	7.05E-10	1.51E-09	8.55E-07	2.769E-06	1.451E-12	0.00E+00	2.28E-10
4 Chromium (Cr III, Cr VI)		0.0098868	0.0004795	0.0119725	0.0119725	15.3149	15.5505			0.0476984	0.12	1.47933
4 COD (g)		4.70E-10		1.544E-10	1.544E-10	9.14E-08	1.70E-07	1.25E-04	1.822E-05	2.907E-09	0.00E+00	1.36E-09
4 Copper (Cu+, Cu++)		0.0018797	0.0001063	0.0028694	0.0028694	3.83402	8.21796	0.007525	0.0128908	0.0078968	6	0.327786
4 Cyanide (CN-)		6.77E-12		1.055E-11	1.055E-11	1.41E-08	3.02E-08			2.902E-11	0.00E+00	5.25E-09
4 Dissolved Matter (unspecified)		4.74E-13		7.386E-13	7.386E-13	9.87E-10	2.12E-09			2.032E-12	0.00E+00	8.56E-09
4 Fluorides (F-)		0.0280664	0.0003473	8.665E-05	8.665E-05	0.0010477	0.0014109			0.002718	0	0.018731
4 Halogenated Matter (organic)		3.76E-05	1.38E-06	7.629E-06	7.629E-06	9.20E-05	1.24E-04			0.0002393	0.00E+00	5.056E-05
4 Hydrocarbons (unspecified)		1.35E-13		2.11E-13	2.11E-13	2.82E-10	6.04E-10			5.805E-13	0.00E+00	0.00E+00
4 Inorganic Dissolved Matter (unspecified)		6.37E-07		7.708E-07	7.708E-07	0.000986	1.00E-03			3.072E-06	0.1	9.31E-05
4 Iron (Fe++, Fe3+)				0	0						0.4	0
4 Lead (Pb++, Pb4+)		7.30E-08	2.68E-09	1.527E-08	1.527E-08	8.69E-07	1.72E-06	9.02E-02	0.0684211	4.642E-07	0.00E+00	1.01E-07
4 Mercury (Hg+, Hg++)		1.35E-12		2.11E-12	2.11E-12	2.82E-09	6.04E-09	1.36E-04	0.0001061	5.805E-12	0.00E+00	5.66E-10
4 Metals (unspecified)		1.56E-15		2.427E-15	2.427E-15	3.24E-12	6.95E-12			6.676E-15	0.00E+00	1.31E-10
4 Nickel (Ni++, Ni3+)		1.61E-05		2.045E-05	2.045E-05	0.0263911	3.31E-02			7.63E-05	0.3	0.0024682
4 Nitrate (NO3-)		6.77E-13		1.055E-12	1.055E-12	1.41E-09	3.02E-09	2.09E-05	4.477E-05	2.902E-12	0.00E+00	6.81E-09
4 Nitrogenous Matter (unspecified, as N)		8.94E-06	3.27E-07	1.899E-06	1.899E-06	0.0001487	3.01E-04			5.686E-05	0.005	1.137E-05
4 Oils (unspecified)		1.83E-11		2.849E-11	2.849E-11	3.81E-08	8.16E-08	2.27E-03	0.0019471	7.837E-11	1.00E-02	0.00E+00
4 Organic Dissolved Matter (unspecified)		0.0004953		0.0001933	0.0001933	0.252978	0.453463			0.0006477	0.1	0.0220024
4 Phenol (C6H5OH)		4.56E-09		1.324E-09	1.324E-09	6.22E-07	1.09E-06			2.844E-08	2.00E-02	0.00E+00
4 Phosphates (PO4 3-, HPO4--, H2PO4-, H3PO4, as P)		4.18E-06		6.521E-06	6.521E-06	0.0087137	1.87E-02			1.794E-05	0.001	0.0007255
4 Polycyclic Aromatic Hydrocarbons (PAH, unspecified)		6.85E-10		1.054E-09	1.054E-09	1.40E-06	3.01E-06	4.48E-03	0.0030512	2.96E-09	5.00E-03	2.81E-05
4 Radioactive Substance (unspecified)		1.62E-12		2.532E-12	2.532E-12	3.38E-09	7.25E-09			6.966E-12	0.00E+00	3.76E-10
4 Salts (unspecified)		9.81E-09		1.53E-08	1.53E-08	2.04E-05	4.38E-05			4.209E-08	0.00E+00	0.00E+00
4 Sodium (Na+)		1.87E-06		2.917E-06	2.917E-06	0.0038983	8.36E-03			8.025E-06	0	0
4 Sulfate (SO4--)		0.0127355	0.0006177	0.0154163	0.0154163	19.7185	20.0197			0.061451	0	1.90489
4 Sulfide (S--)		8.03E-06	2.92E-07	1.761E-06	1.761E-06	0.0002175	4.51E-04			5.099E-05	0.01	1.323E-05
4 Suspended Matter (unspecified)		9.52E-10		2.827E-10	2.827E-10	1.39E-07	2.44E-07			5.933E-09	0.00E+00	0.00E+00
4 TDS (g)		0.0010039	0.0001037	0.0015405	0.0015405	2.05753	4.41017	0.235027	0.0436469	0.0042576	0.3	0.211864
4 TOC (Total Organic Carbon)				0	0						0	0
4 Toluene (C6H5CH3)		1.01E-09		1.583E-09	1.583E-09	2.11E-06	4.53E-06			4.354E-09	0.00E+00	0.00E+00
4 Water: Chemically Polluted		1.49E-11		2.321E-11	2.321E-11	3.10E-08	6.65E-08			6.385E-11	0.00E+00	2.30E-08
4 Zinc (Zn++)		0.0015216		0.0019011	0.0019011	2.44668	2.87775			0.0072515	0	0.185509
		1.16E-10		4.233E-11	4.233E-11	2.92E-08	5.63E-08	6.93E-04	-3.36E-05	7.083E-10	0.00E+00	7.15E-08

Appendix C. Fly Ash through Superplasticizer

per unit	Fly Ash	Coal Production (under-ground mined)	Coal Combus-tion (US mix)	Sand	Gravel	Diesel fuel production	Gasoline production	Rebar Steel	EAF steel (section)	Electricity (US grid)	PVA fiber	Super-Plastcizer (as Formaldehyde)
3 Calcium (Ca)		8.52E-07	7.80E-06	1.732E-07	1.732E-07	2.18E-06	3.00E-06	5.66E-05	6.504E-05	5.43E-06	0.00E+00	4.86E-06
3 Carbon Dioxide (CO2)		3.10E-08		3.757E-08	3.757E-08	4.81E-05	4.88E-05			1.497E-07	0.00E+00	0.00E+00
3 Carbon Disulfide (CS2)		48.5529	366.768	10.520928	10.520928	385.543	670.25	417.9409	441.662	253.947	3400	1461.85
3 Carbon Monoxide (CO)		9.59E-07		1.948E-07	1.948E-07	2.35E-06	3.16E-06			6.111E-06	0.00E+00	3.49E-05
3 Chlorides (Cl-)		0.06795	0.0423162	0.0149188	0.0149188	1.07361	2.00253	3.73899	4.56849	0.115789	0.8	11.0802
3 Chlorine (Cl2)		1.20E-05		2.48E-06	2.48E-06	8.44E-05	1.57E-04			7.663E-05	0.00E+00	0
3 Chloroacetophenone (2-C8H7ClO)		9.82E-11		2.852E-11	2.852E-11	1.34E-08	2.35E-08			6.126E-10	0.00E+00	3.32E-06
3 Chlorobenzene (C6H5Cl)		5.17E-08		1.049E-08	1.049E-08	1.27E-07	1.70E-07			3.291E-07	0.00E+00	0.00E+00
3 Chloroform (CHCl3, HC-20)		1.62E-07		3.297E-08	3.297E-08	3.98E-07	5.36E-07			1.034E-06	0.00E+00	6.40E-07
3 Chromium (Cr III, Cr VI)		4.35E-07		8.842E-08	8.842E-08	1.07E-06	1.44E-06			2.774E-06	0.00E+00	8.07E-07
3 Chrysene (C18H12)		2.17E-05		4.414E-06	4.414E-06	5.72E-05	7.66E-05	1.13E-03	0.0008666	0.0001384	0.00E+00	7.79E-05
3 Cobalt (Co)		7.41E-10		7.224E-08	7.224E-08	3.15E-09	4.82E-09			4.722E-09	0.00E+00	0.00E+00
3 Copper (Cu)		9.52E-07	6.07E-06	1.963E-07	1.963E-07	6.84E-06	8.82E-06			6.061E-06	0.00E+00	5.94E-05
3 Cumene (C9H12)		9.17E-08		2.128E-08	2.128E-08	4.29E-06	5.13E-06			5.804E-07	0.00E+00	1.79E-05
3 Cyanide (CN-)		3.91E-08		7.943E-09	7.943E-09	9.58E-08	1.29E-07			2.492E-07	0.00E+00	1.04E-06
3 Di(2-ethylhexyl)phthalate (DEHP, C24H38O4)		1.84E-05		3.747E-06	3.747E-06	4.52E-05	6.09E-05			0.0001175	0.00E+00	3.80E-07
3 Dibenzo(a,h)anthracene		5.39E-07		1.094E-07	1.094E-07	1.32E-06	1.78E-06			3.432E-06	0.00E+00	2.21E-08
3 Dichlorobenzene (1,4-C6H4Cl2)		2.37E-12		2.254E-09	2.254E-09	9.01E-10	1.61E-09			1.42E-11	0.00E+00	0.00E+00
3 Dimethyl Benzanthracene (7,12-C20H16)		2.28E-09		9.604E-10	9.604E-10	7.68E-07	1.32E-06			1.377E-08	0.00E+00	1.45E-08
3 Dimethyl Sulfate (C2H6O4S)		2.96E-11		1.223E-11	1.223E-11	9.61E-09	1.66E-08			1.793E-10	0.00E+00	0.00E+00
3 Dinitrotoluene (2,4-C7H6N2O4)		3.54E-07		7.193E-08	7.193E-08	8.68E-07	1.17E-06			2.257E-06	0.00E+00	1.10E-08
3 Dioxins (unspecified) (TEq)		2.07E-09		4.196E-10	4.196E-10	5.06E-09	6.82E-09			1.316E-08	0.00E+00	1.40E-08
3 Diphenyl ((C6H5)2)		1.19E-10		2.426E-11	2.426E-11	2.93E-10	3.94E-10	2.83E-09	2.485E-09	7.611E-10	0.00E+00	0.00E+00
3 Ethane (C2H6)		1.25E-08		2.548E-09	2.548E-09	3.07E-08	4.14E-08			7.992E-08	0.00E+00	0.00E+00
3 Ethyl Benzene (C6H5C2H5)		5.89E-06		3.844E-06	3.844E-06	0.0019846	3.42E-03			3.558E-05	0	0
3 Ethyl Chloride (C2H5Cl)		6.96E-07		2.998E-06	2.998E-06	1.71E-06	2.32E-06			4.433E-06	0.00E+00	1.40E-06
3 Ethylene Dibromide (C2H4Br2)		3.10E-07		6.294E-08	6.294E-08	7.59E-07	1.02E-06			1.974E-06	0.00E+00	0.00E+00
3 Ethylene Dichloride (C2H4Cl2)		8.86E-09		1.798E-09	1.798E-09	2.17E-08	2.92E-08			5.641E-08	0.00E+00	0.00E+00
3 Fluoranthene		2.95E-07		5.994E-08	5.994E-08	7.23E-07	9.74E-07			1.88E-06	0.00E+00	2.27E-08
3 Fluorene (C13H10)		5.25E-09		6.791E-07	6.791E-07	1.51E-08	2.14E-08			3.341E-08	0.00E+00	0.00E+00
3 Fluorides (F-)		6.72E-09		4.834E-07	4.834E-07	1.86E-08	2.60E-08			4.281E-08	0.00E+00	7.41E-09
3 Formaldehyde (CH2O)		1.49E-06		3.067E-07	3.067E-07	9.56E-06	1.75E-05			9.494E-06	0.00E+00	1.31E-06
3 Furan (C4H4O)		1.99E-05	1.48E-05	0.0001232	0.0001232	0.0033148	3.43E-03			0.0001233	0	0.74036
3 Halogenated Hydrocarbons (unspecified)		5.55E-10		1.128E-10	1.128E-10	1.36E-09	1.83E-09			3.539E-09	0.00E+00	0.00E+00
3 Halon 1301 (CF3Br)		3.38E-16		5.276E-16	5.276E-16	7.05E-13	1.51E-12			1.451E-15	0.00E+00	2.16E+00
3 Hexane (C6H14)		5.89E-13		9.18E-13	9.18E-13	1.23E-09	2.63E-09			2.525E-12	0.00E+00	0.00E+00
3 Hydrocarbons (NMHC)		3.92E-06		9.397E-06	9.397E-06	0.0011536	1.99E-03			2.381E-05	0	0
3 Hydrogen (H2)		0.0370682	0.0117571	0.0021636	0.0021636	0.716786	0.917549			0.0122539	21	0
3 Hydrogen Chloride (HCl)		0.0045692		0	0						0.001	0
3 Hydrogen Fluoride (HF)		0.0088553	0.0727274	0.0017983	0.0017983	0.0217028	0.0292291	0.0038848	0.0214677	0.0564136	0.06	0.0116063
3 Hydrogen Sulfide (H2S)		0.0011069	0.0090909	0.0002248	0.0002248	0.0027119	0.0036516			0.0070517	0.001	0.0014507
3 Indeno (1,2,3,c,d) Pyrene		5.62E-06	2.44E-07	6.81E-06	6.81E-06	0.0087105	8.84E-03	8.63E-04	0.0012654	2.713E-05	0	0.000748
3 Iron (Fe)		4.54E-10		2.712E-08	2.712E-08	2.42E-09	3.83E-09			2.889E-09	0.00E+00	0.00E+00
3 Isophorone		6.92E-08		8.382E-08	8.382E-08	0.0001072	1.09E-04			3.339E-07	0	0
3 Lead (Pb)		4.28E-06		8.692E-07	8.692E-07	1.05E-05	1.41E-05			2.727E-05	0.00E+00	0.00E+00
3 Magnesium (Mg)		1.29E-05	0.0001982	2.62E-06	2.62E-06	3.34E-05	4.49E-05	0.0017399	0.0019847	8.215E-05	0.00E+00	4.71E-05
3 Manganese (Mn)		8.12E-05	0.0006667	1.648E-05	1.648E-05	0.0001989	2.68E-04			0.0005171	0	0.0001061
3 Mercury (Hg)		2.43E-05	0.0002443	4.931E-06	4.931E-06	6.02E-05	8.16E-05			0.0001547	0.00E+00	6.92E-05
3 Metals (unspecified)		8.13E-07	7.31E-06	1.679E-07	1.679E-07	2.34E-06	3.18E-06	1.25E-04	0.0001013	5.179E-06	0.00E+00	2.26E-06
3 Methane (CH4) (g)		4.55E-10		5.852E-10	5.852E-10	7.57E-07	1.62E-06			2.144E-09	1.00E-03	0.00E+00
3 Methyl Bromide (CH3Br)		4.42956	0.0127201	0.0168091	0.0168091	2.21258	3.34023	0.750859	0.717332	0.481498	0	7.71785
3 Methyl Chloride (CH3Cl)		1.18E-06		2.398E-07	2.398E-07	2.89E-06	3.89E-06			7.522E-06	0.00E+00	0.00E+00
3 Methyl Cholanthrene (3-C21H16)		3.91E-06		7.943E-07	7.943E-07	9.58E-06	1.29E-05			2.492E-05	0.00E+00	0.00E+00
3 Methyl Chrysene (5-C19H15)		3.42E-12		1.441E-12	1.441E-12	1.15E-09	1.99E-09			2.066E-11	0.00E+00	0.00E+00
3 Methyl Ethyl Ketone (MEK, C4H8O)		1.62E-10		3.297E-11	3.297E-11	3.98E-10	5.36E-10			1.034E-09	0.00E+00	0.00E+00
3 Methyl Hydrazine (CH6N2)		2.88E-06		5.845E-07	5.845E-07	7.05E-06	9.49E-06			1.833E-05	0.00E+00	5.79E-06
3 Methyl Methacrylate (CH2C(CH3)COOCH3)		1.25E-06		2.548E-07	2.548E-07	3.07E-06	4.14E-06			7.992E-06	0.00E+00	0.00E+00
3 Methyl Naphthalene (2-C11H10)		1.48E-07		2.997E-08	2.997E-08	3.61E-07	4.87E-07			9.402E-07	0.00E+00	7.44E-07
3 Methyl tert Butyl Ether (MTBE, C5H12O)		4.56E-11		1.921E-11	1.921E-11	1.54E-08	2.65E-08			2.755E-10	0.00E+00	0.00E+00
3 Methylene Chloride (CH2Cl2, HC-130)		2.58E-07		5.245E-08	5.245E-08	6.33E-07	8.52E-07			1.645E-06	0.00E+00	4.45E-07
3 Molybdenum (Mo)		2.14E-06		4.346E-07	4.346E-07	5.24E-06	7.06E-06			1.363E-05	0.00E+00	0.00E+00
3 Naphthalene (C10H8)		5.89E-08		1.539E-08	1.539E-08	5.40E-06	6.16E-06			3.7E-07	0.00E+00	9.61E-06
3 Nickel (Ni)		1.36E-07		4.659E-06	4.659E-06	9.00E-07	1.50E-06			8.677E-07	0.00E+00	8.12E-07
3 Nitrogen oxides (Nox) (g)		2.03E-05		4.314E-06	4.314E-06	0.0003415	3.79E-04			0.000129	0	0.0008844
3 Nitrous Oxide (N2O)		0.275592	1.16163	0.0566773	0.0566773	1.51217	2.25591	1.02586	0.894316	0.92498	57	3.69992
3 Organic Matter (unspecified)		0.0089879	0.0069196	0.0010713	0.0010713	0.0446547	0.0542972	0.0210801	0.0145929	0.0329211	0	0.0253916
3 Particulates (unspecified)		0.0015485	0.0023364	0.0003847	0.0003847	0.182259	0.315271			0.0082301	0.005	0.888311
3 Pentane (C5H12)		0.110021	1.55621	0.000493	0.000493	0.3407	0.506966	0.2197928	0.347969	0.0082301	2	0.694763
3 Phenanthrene (C14H10)		4.94E-06		2.081E-06	2.081E-06	0.0016645	2.87E-03			2.984E-05	0	0
3 Phenol (C6H5OH)		2.00E-08		1.342E-06	1.342E-06	6.05E-08	8.63E-08			1.271E-07	0.00E+00	2.45E-08
3 Phosphorus (P)		1.18E-07		2.398E-08	2.398E-08	2.89E-07	3.89E-07			7.522E-07	0.00E+00	1.64E-06
3 PM10 (g)		3.49E-07		9.306E-08	9.306E-08	3.48E-05	3.73E-05			2.191E-06	0.00E+00	9.95E-10
3 PM2.5 (g)		4.13E-07		0.0012649	0.0012649	0.0006394	6.49E-04	2.07E-01	0.3284827	1.991E-06	0	0.000188
3 Polycyclic Aromatic Hydrocarbons (PAH, unspecified)				0	0						0	0

Appendix C. Truck Transport through Landfilling

per unit	Truck transportation	Rail transportation	Sea Tanker transportation	Cement 1 - wet	Cement 2- long-dry	Cement 3 - dry with pre-heater	Cement 4 - dry, pre-calciner & preheater	Cement 5 - weighted average	Rubber	wood	Epoxy	landfilling
1 Barium Sulfate (BaSO4, in ground)	1 kg-km	1 kg-km	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
1 Bauxite (Al2O3, ore)	0		8.98E-11									
1 Calcium Sulfate (CaSO4, ore)	0	5.05E-10		6.113E-07	6.113E-07	6.113E-07	6.113E-07	6.113E-07	3.71E-04	5.60E-06	2.02E-04	6.12E-08
1 Clay (in ground)	0			0.05	0.05	0.05	0.05	0.05				
1 Coal (in ground)	0			0.049	0.064	0.102	0.063	0.068	2.046E-05	0.000036	1.562E-05	0.274495
1 Diesel fuel	0	1.70E-07	6.46E-08	0.0913229	0.0913229	0.0913229	0.0913229	0.0913229	0.094078	0.00033	0.25949	0.0002814
1 Dolomite (in ground)	2.892E-05											0.007289
1 E Feedstock Energy	0											
1 E Fuel Energy	-0.001025	7.38E-06	6.25E-06	0.0901589	0.0901589	0.0901589	0.0901589	0.0901589	58.1855	17.78	44.9561	
1 E Non Renewable Energy	0.0010248	0.0002361	0.000099	3.65385	3.65385	3.65385	3.65385	3.65385	26.029	10.67	34.9216	
1 E Renewable Energy	0	0.0002433	0.0001052	3.69485	3.69485	3.69485	3.69485	3.69485	83.9855	4.54	79.023	
1 E Total Primary Energy	0	2.30E-07	8.74E-08	0.0478058	0.0478058	0.0478058	0.0478058	0.0478058	0.21468	23.91	0.857736	
1 Electricity	0.0010248	0.0002435	0.0001052	6.57	6.07	4.9	4.52	5.32	84.200333	2.85E+01	7.99E+01	0.26842
1 Ferrous Scrap	0			0.506	0.563	0.586	0.541	0.546	1.7213667		5.57164	
1 Gypsum	0											
1 Iron (Fe, ore)	0			0.059	0.048	0.051	0.048	0.051				
1 lignite	0			0.004	0.012	0.004	0.008	0.007	0.0002084	0.00081	0.000694	0.0001143
1 Limestone (CaCO3, in ground)	0											
1 Natural Gas (in ground)	0	1.35E-08	5.11E-09	1.142	1.239	1.037	1.273	1.192	0.0128459	0.00025	0.190776	0.0000545
1 Oil (in ground)	0	5.51E-07	1.72E-07	0.00738	0.00805	0.00651	0.0116	0.00905	0.901755		0.745525	0.0003191
1 Raw Materials (unspecified)	0	5.00E-06	2.32E-06	0.0117877	0.0117877	0.0117877	0.0117877	0.0117877	0.8635333		0.667638	0.0023276
1 Sand (in ground)	0			3.4	2.14	2.07	2.07	2.37				
1 Sodium Chloride (NaCl, in ground or in sea)	0	3.09E-10	5.5E-11	0.019	0.011	0	0.022	0.014		0.0000016	0.0002014	0.0909573
1 Sulfur (S, in ground)	0	1.42E-10	2.53E-11	1.719E-07	1.719E-07	1.719E-07	1.719E-07	1.719E-07	0.0063647		9.09E-01	5.25E-06
1 shale	0											
1 Uranium (U, ore)	0			0.094	0.032	0.022	0.059	0.054				
1 Water Used (total)	0	2.87E-12	1.09E-12	5.952E-07	5.952E-07	5.952E-07	5.952E-07	5.952E-07	1.802E-06		8.56E-07	4.20E-09
1 Zinc (Zn)	0	0.0001186	0.0000213	0.819	0.1465	0.1465	0.1465	0.176	4.7685333	0.33	4.67493	
2 Non-Allocted by products	0									6.00E-08		
2 Recovered Matter (total)	0											
2 Recovered Matter: Aluminum Scrap	0	8.58E-09	3.26E-09	0.0033192	0.0033192	0.0033192	0.0033192	0.0033192				
2 Recovered Matter: Ash	0	2.05E-12	3.65E-13	2.49E-09	2.487E-09	2.487E-09	2.487E-09	2.487E-09				
2 Waste (hazardous)	0	8.58E-09	3.26E-09	0.0033192	0.0033192	0.0033192	0.0033192	0.0033192				
2 Waste (municipal and industrial)	0	6.94E-09	1.23E-09	8.40E-06	8.398E-06	8.398E-06	8.398E-06	8.398E-06			2.17E-05	
2 Waste (total)	0	1.13E-08	2.02E-09	1.37E-05	1.372E-05	1.372E-05	1.372E-05	1.372E-05	0.0013991	0.01216	1.95E-03	
2 Waste (unspecified)	0	9.14E-07	3.53E-07	0.320628	0.320628	0.320628	0.320628	0.320628	0.0370758	0.01836	0.129363	
2 Waste (unspecified, to incineration)	0	4.23E-08	1.61E-08	0.0090098	0.0090098	0.0090098	0.0090098	0.0090098	0.021678		0.0343092	
2 Waste: Bauxite Residues (red mud)	0	1.75E-10	1.01E-08	4.05E-07	4.048E-07	4.048E-07	4.048E-07	4.048E-07				
2 Waste: FGD Sludge	0	1.37E-10	2.44E-11	1.66E-07	1.659E-07	1.659E-07	1.659E-07	1.659E-07				
2 Waste: Mineral (inert)	0	2.65E-09	1E-09	0.0005531	0.0005531	0.0005531	0.0005531	0.0005531	0.0014873		0.0007068	
2 Waste: Non Toxic Chemicals (unspecified)	0	2.94E-11	5.23E-12	3.56E-08	3.56E-08	3.56E-08	3.56E-08	3.56E-08	0.0048622	0.0046	6.80E-02	
2 Waste: Slags and Ash (unspecified)	0	6.89E-12	1.23E-12	8.34E-09	8.343E-09	8.343E-09	8.343E-09	8.343E-09	0.0014134		5.60E-04	
2 Waste: mining + tailing	0	8.35E-07	3.17E-07	0.178028	0.178028	0.178028	0.178028	0.178028	0.0069256	0.0016	0.0137628	
3 (ar) Radioactive Substance (unspecified)	0											
3 Acenaphthene (C12H10)	0	1.04E-08	1.84E-09	1.25E-05	1.255E-05	1.255E-05	1.255E-05	1.255E-05				
3 Acenaphthylene (C12H8)	0	6.45E-14	2.08E-14	4.43E-08	4.433E-08	4.433E-08	4.433E-08	4.433E-08				
3 Acetaldehyde (CH3CHO)	0	2.68E-14	9.63E-15	1.17E-08	1.172E-08	1.172E-08	1.172E-08	1.172E-08				
3 Acetophenone (C8H8O)	1.192E-06	4.84E-11	1.84E-11	2.60E-05	2.597E-05	2.597E-05	2.597E-05	2.597E-05				
3 Acrolein (CH2CHCHO)	0	1.27E-12	4.84E-13	6.83E-07	6.834E-07	6.834E-07	6.834E-07	6.834E-07				
3 Aldehyde (unspecified)	0.0000001	2.46E-11	9.35E-12	1.32E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05				
3 Aluminum (Al)	0	1.79E-08	5.08E-09	0.0025638	0.0025638	0.0025638	0.0025638	0.0025638	0.0002815		0.0001204	0.0016699
3 Ammonia (NH3)	0	2.61E-10	1.51E-08	6.02E-07	6.023E-07	6.023E-07	6.023E-07	6.023E-07				
3 Anthracene (C14H10)	0	2.60E-08	7E-09	0.0003938	0.0003938	0.0003938	0.0003938	0.0003938	3.223E-05	0.0000012	8.294E-06	0.00005
3 Antimony (Sb)	0	2.60E-14	8.98E-15	1.09E-08	1.089E-08	1.089E-08	1.089E-08	1.089E-08				
3 Aromatic Hydrocarbons (unspecified)	0	7.53E-12	2.08E-12	6.48E-06	6.484E-06	6.484E-06	6.484E-06	6.484E-06				
3 Arsenic (As)	0	5.96E-13	1.06E-13	7.22E-10	7.22E-10	7.22E-10	7.22E-10	7.22E-10				
3 Barium (Ba)	0	1.77E-10	1.57E-09	9.50E-05	9.5E-05	9.5E-05	9.5E-05	9.5E-05				
3 Benzene (C6H6)	0	3.92E-12	1.05E-12	2.86E-06	2.861E-06	2.861E-06	2.861E-06	2.861E-06				
3 Benzo(a)anthracene	2.4E-08	1.77E-07	4.89E-08	0.0018087	0.0018087	0.0018087	0.0018087	0.0018087				0.0001866
3 Benzo(a)pyrene (C20H12)	0	1.52E-14	4.66E-15	7.72E-09	7.717E-09	7.717E-09	7.717E-09	7.717E-09				
3 Benzo(b)fluoranthene	1.2E-10	2.35E-11	3.05E-15	1.79E-09	1.787E-09	1.787E-09	1.787E-09	1.787E-09				
3 Benzo(bjk)fluoranthene	0	5.97E-15	1.64E-15	8.14E-10	8.145E-10	8.145E-10	8.145E-10	8.145E-10				
3 Benzo(ghi)perylene	0	9.34E-15	3.55E-15	5.01E-09	5.011E-09	5.011E-09	5.011E-09	5.011E-09				
3 Benzo(k)fluoranthene	0	6.75E-15	2.05E-15	2.41E-09	2.407E-09	2.407E-09	2.407E-09	2.407E-09				
3 Benzyl Chloride (C7H7Cl)	0	5.97E-15	1.64E-15	8.14E-10	8.145E-10	8.145E-10	8.145E-10	8.145E-10				
3 Beryllium (Be)	0	5.95E-11	2.26E-11	3.19E-05	3.189E-05	3.189E-05	3.189E-05	3.189E-05				
3 Bromoform (CHBr3)	0	1.78E-11	6.68E-12	9.40E-06	9.402E-06	9.402E-06	9.402E-06	9.402E-06				
3 Butane (C4H10)	0	3.31E-12	1.26E-12	1.78E-06	1.777E-06	1.777E-06	1.777E-06	1.777E-06				
3 Cadmium (Cd)	0	6.32E-09	1.79E-09	9.01E-05	9.01E-05	9.01E-05	9.01E-05	9.01E-05				

Appendix C. Truck Transport through Landfilling

per unit	Truck transportation	Rail transportation	Sea Tanker transportation	Cement 1 - wet	Cement 2- long-dry	Cement 3 - dry with pre-heater	Cement 4 - dry, pre-calciner & preheater	Cement 5 - weighted average	Rubber	wood	Epoxy	landfilling
3 Calcium (Ca)	1.3E-09	1.02E-11	3.8E-12	1.01E-05	1.006E-05	1.006E-05	1.006E-05	1.006E-05			3.47E-06	
3 Carbon Dioxide (CO2)	0	2.26E-10	1.31E-08	5.22E-07	5.22E-07	5.22E-07	5.22E-07	5.22E-07				
3 Carbon Disulfide (CS2)	0.0756	0.0165936	0.0072599	997.3	930.1	866.3	852.3	900.5	1493.0317	770	2093.38	19.785
3 Carbon Monoxide (CO)	0	1.10E-11	4.19E-12	5.92E-06	5.922E-06	5.922E-06	5.922E-06	5.922E-06				
3 Chlorides (Cl-)	0.00019	5.20E-05	0.0000128	0.097	0.135	0.511	1.799	0.876	1.2405283	5.7	1.25666	0.1475891
3 Chlorine (Cl2)	0	3.96E-10	9.91E-11	3.74E-04	0.0003744	0.0003744	0.0003744	0.0003744				
3 Chloroacetophenone (2-C8H7ClO)	0	6.29E-14	1.77E-14	6.48E-10	6.479E-10	6.479E-10	6.479E-10	6.479E-10				
3 Chlorobenzene (C6H5Cl)	0	5.95E-13	2.26E-13	3.19E-07	3.189E-07	3.189E-07	3.189E-07	3.189E-07				
3 Chloroform (CHCl3, HC-20)	0	1.87E-12	7.09E-13	1.00E-06	1.002E-06	1.002E-06	1.002E-06	1.002E-06				
3 Chromium (Cr III, Cr VI)	0	5.01E-12	1.9E-12	2.69E-06	2.688E-06	2.688E-06	2.688E-06	2.688E-06				4.13E-06
3 Chrysene (C18H12)	0	2.69E-10	8.52E-10	0.0002478	0.0002478	0.0002478	0.0002478	0.0002478				
3 Cobalt (Co)	0	1.48E-14	4.92E-15	5.82E-09	5.818E-09	5.818E-09	5.818E-09	5.818E-09				
3 Copper (Cu)	0	3.22E-11	9.63E-10	1.11E-05	1.11E-05	1.11E-05	1.11E-05	1.11E-05				
3 Cumene (C9H12)	0	2.02E-11	8.88E-10	2.04E-06	2.035E-06	2.035E-06	2.035E-06	2.035E-06				
3 Cyanide (CN-)	0	4.50E-13	1.71E-13	2.41E-07	2.415E-07	2.415E-07	2.415E-07	2.415E-07				
3 Di(2-ethylhexyl)phthalate (DEHP, C24H38O4)	0	2.12E-10	8.06E-11	0.0001139	0.0001139	0.0001139	0.0001139	0.0001139				
3 Dibenzo(a,h)anthracene	0	6.20E-12	2.35E-12	3.33E-06	3.326E-06	3.326E-06	3.326E-06	3.326E-06				
3 Dichlorobenzene (1,4-C6H4Cl2)	0	4.23E-15	1.14E-15	8.83E-10	8.834E-10	8.834E-10	8.834E-10	8.834E-10				
3 Dimethyl Benzanthracene (7,12-C20H16)	0	3.61E-12	1.02E-12	5.15E-08	5.148E-08	5.148E-08	5.148E-08	5.148E-08				
3 Dimethyl Sulfate (C2H6O4S)	0	4.51E-14	1.28E-14	6.46E-10	6.462E-10	6.462E-10	6.462E-10	6.462E-10				
3 Dinitrotoluene (2,4-C7H6N2O4)	0	4.08E-12	1.55E-12	2.19E-06	2.187E-06	2.187E-06	2.187E-06	2.187E-06				
3 Dioxins (unspecified) (TEq)	0	2.38E-14	9.03E-15									
3 Diphenyl ((C6H5)2)	0	1.38E-15	5.22E-16	9.75E-08	5.583E-07	3.56E-09	9.927E-08	1.64E-07				
3 Ethane (C2H6)	0	1.44E-13	5.48E-14	7.74E-08	7.745E-08	7.745E-08	7.745E-08	7.745E-08				
3 Ethyl Benzene (C6H5C2H5)	0	9.33E-09	2.65E-09	1.33E-04	0.000133	0.000133	0.000133	0.000133				2.384E-05
3 Ethyl Chloride (C2H5Cl)	0	8.06E-12	3.05E-12	4.35E-06	4.351E-06	4.351E-06	4.351E-06	4.351E-06				4.52E-04
3 Ethylene Dibromide (C2H4Br2)	0	3.57E-12	1.35E-12	1.91E-06	1.913E-06	1.913E-06	1.913E-06	1.913E-06				
3 Ethylene Dichloride (C2H4Cl2)	0	1.02E-13	3.87E-14	5.47E-08	5.467E-08	5.467E-08	5.467E-08	5.467E-08				
3 Fluoranthene	0	3.40E-12	1.29E-12	1.82E-06	1.822E-06	1.822E-06	1.822E-06	1.822E-06				4.58E-05
3 Fluorene (C13H10)	0	7.11E-14	2.58E-14	3.49E-08	3.489E-08	3.489E-08	3.489E-08	3.489E-08				
3 Fluorides (F-)	0	8.74E-14	3.2E-14	4.38E-08	4.38E-08	4.38E-08	4.38E-08	4.38E-08				
3 Formaldehyde (CH2O)	0	4.50E-11	1.15E-11	4.07E-05	4.072E-05	4.072E-05	4.072E-05	4.072E-05	1.428E-06	0.000018	6.78E-07	
3 Furan (C4H4O)	3.42E-06	1.56E-08	7.14E-09	0.000138	0.000138	0.000138	0.000138	0.000138	4.232E-06		2.011E-06	
3 Halogenated Hydrocarbons (unspecified)	0	6.40E-15	2.43E-15	0.00E+00	0	0	0	0				
3 Halon 1301 (CF3Br)	0	3.31E-18	5.89E-19	4.01E-15	4.011E-15	4.011E-15	4.011E-15	4.011E-15				
3 Hexane (C6H14)	0	5.77E-15	1.03E-15	6.98E-12	6.979E-12	6.979E-12	6.979E-12	6.979E-12				
3 Hydrocarbons (NMHC)	0	5.42E-09	1.54E-09	8.03E-05	8.028E-05	8.028E-05	8.028E-05	8.028E-05				
3 Hydrogen (H2)	0.0000912	1.92E-05	4.23E-06	0.0809178	0.0809178	0.0809178	0.0809178	0.0809178	5.0066667	1.7	8.43204	0.0226134
3 Hydrogen Chloride (HCl)	0								0.000752			
3 Hydrogen Fluoride (HF)	0	1.02E-07	3.87E-08	0.04	0.06	0.13	0.06	0.07	0.0109838	0.011	0.175922	0.0113185
3 Hydrogen Sulfide (H2S)	0	1.27E-08	4.84E-09	0.006834	0.006834	0.006834	0.006834	0.006834		0.00052	1.173E-10	
3 Indeno (1,2,3,c,d) Pyrene	0	4.09E-08	1.9E-08	9.46E-05	9.46E-05	9.46E-05	9.46E-05	9.46E-05	0.0028544	0.0000008	5.76E-03	1.11E-03
3 Iron (Fe)	0	1.14E-14	3.65E-15	3.92E-09	3.922E-09	3.922E-09	3.922E-09	3.922E-09				
3 Isophorone	0	5.04E-10	2.92E-08	1.16E-06	1.164E-06	1.164E-06	1.164E-06	1.164E-06				
3 Lead (Pb)	0	4.93E-11	1.87E-11	2.64E-05	2.642E-05	2.642E-05	2.642E-05	2.642E-05				
3 Magnesium (Mg)	5.8E-09	1.57E-10	3.9E-10	1.84E-04	0.0001836	0.0001836	0.0001836	0.0001836			4.51E-05	
3 Manganese (Mn)	0	9.35E-10	3.55E-10	0.0005012	0.0005012	0.0005012	0.0005012	0.0005012				
3 Mercury (Hg)	0	2.83E-10	1.07E-10	0.0001716	0.0001716	0.0001716	0.0001716	0.0001716				
3 Metals (unspecified)	0	1.10E-11	4.81E-11	5.51E-05	8.342E-05	2.691E-05	6.941E-05	6.057E-05			1.222E-06	
3 Methane (CH4) (g)	0	3.56E-12	6.4E-13	4.89E-09	4.886E-09	4.886E-09	4.886E-09	4.886E-09	0.0013616	0.011	3.18E-03	
3 Methyl Bromide (CH3Br)	2.88E-06	1.13E-05	3.52E-06	0.055	0.011	0.004	0.051	0.035	3.6969333		7.86262	0.0012406
3 Methyl Chloride (CH3Cl)	0	1.36E-11	5.16E-12	7.29E-06	7.289E-06	7.289E-06	7.289E-06	7.289E-06				
3 Methyl Cholanthrene (3-C21H16)	0	4.50E-11	1.71E-11	2.41E-05	2.415E-05	2.415E-05	2.415E-05	2.415E-05				
3 Methyl Chrysene (5-C19H15)	0	5.42E-15	1.54E-15	7.72E-11	7.723E-11	7.723E-11	7.723E-11	7.723E-11				
3 Methyl Ethyl Ketone (MEK, C4H8O)	0	1.87E-15	7.09E-16	1.00E-09	1.002E-09	1.002E-09	1.002E-09	1.002E-09				
3 Methyl Hydrazine (CH6N2)	0.0000005	3.31E-11	1.26E-11	1.78E-05	1.777E-05	1.777E-05	1.777E-05	1.777E-05				
3 Methyl Methacrylate (CH2C(CH3)COOCH3)	0	1.44E-11	5.48E-12	7.74E-06	7.745E-06	7.745E-06	7.745E-06	7.745E-06				
3 Methyl Naphthalene (2-C11H10)	0	1.70E-12	6.45E-13	9.11E-07	9.111E-07	9.111E-07	9.111E-07	9.111E-07				
3 Methyl tert Butyl Ether (MTBE, C5H12O)	0	7.22E-14	2.05E-14	1.03E-09	1.03E-09	1.03E-09	1.03E-09	1.03E-09				
3 Methylene Chloride (CH2Cl2, HC-130)	0	2.97E-12	1.13E-12	1.59E-06	1.594E-06	1.594E-06	1.594E-06	1.594E-06				
3 Molybdenum (Mo)	0	2.46E-11	9.35E-12	1.32E-05	1.321E-05	1.321E-05	1.321E-05	1.321E-05				
3 Naphthalene (C10H8)	0	2.54E-11	1.21E-09	1.01E-06	1.008E-06	1.008E-06	1.008E-06	1.008E-06				
3 Nickel (Ni)	0	4.23E-12	1.26E-12	1.84E-06	1.838E-06	1.838E-06	1.838E-06	1.838E-06				
3 Nitrogen oxides (Nox) (g)	0	1.60E-09	7.57E-08	0.0003354	0.0003354	0.0003354	0.0003354	0.0003354				
3 Nitrous Oxide (N2O)	0.000984	0.0002139	0.0000973	3.53	2.898	2.333	2.044	2.577	8.6982333	2.4	13.0246	0.2107511
3 Organic Matter (unspecified)	0.0000106	6.80E-07	8.67E-08	0.0153601	0.0153601	0.0153601	0.0153601	0.0153601	0.050488		0.022515	
3 Particulates (unspecified)	0	8.57E-07	2.42E-07	0.008789	0.008789	0.008789	0.008789	0.008789	0.0017369	0.01	0.0007084	
3 Pentane (C5H12)	0.0000504	1.10E-05	0.000006	2.465	2.553	2.47	2.513	2.502	1.8507	1	17.123	0.015263
3 Phenanthrene (C14H10)	0	7.82E-09	2.22E-09	1.12E-04	0.0001116	0.0001116	0.0001116	0.0001116				
3 Phenol (C6H5OH)	0	2.84E-13	1.02E-13	1.29E-07	1.29E-07	1.29E-07	1.29E-07	1.29E-07				
3 Phosphorus (P)	0	1.36E-12	5.16E-13	7.29E-07	7.289E-07	7.289E-07	7.289E-07	7.289E-07				
3 PM10 (g)	0	1.64E-10	8.87E-09	1.06E-05	1.056E-05	1.056E-05	1.056E-05	1.056E-05				
3 PM2.5 (g)	0	3.00E-09		6.94E-06	6.944E-06	6.944E-06	6.944E-06	6.944E-06				3.49E-02
3 Polycyclic Aromatic Hydrocarbons (PAH, unspe	0											

Appendix C. Truck Transport through Landfilling

per unit	Truck transportation	Rail transportation	Sea Tanker transportation	Cement 1 - wet	Cement 2- long-dry	Cement 3 - dry with pre-heater	Cement 4 - dry, pre-calciner & preheater	Cement 5 - weighted average	Rubber	wood	Epoxy	landfilling
4 COD (g)	0	4.30E-13	1.07E-13	3.19E-09	3.19E-09	3.19E-09	3.19E-09	3.19E-09		0.038	6.02E-06	3.60E-07
4 Copper (Cu+, Cu++)	0	1.80E-05	0.0000032	0.0218175	0.0218175	0.0218175	0.0218175	0.0218175	0.4480333		0.174422	0.0008
4 Cyanide (CN-)	0	6.63E-14	1.18E-14	8.02E-11	8.022E-11	8.022E-11	8.022E-11	8.022E-11				
4 Dissolved Matter (unspecified)	0	4.64E-15	8.25E-16	5.62E-12	5.615E-12	5.615E-12	5.615E-12	5.615E-12				
4 Fluorides (F-)	0	4.92E-09	1.87E-09	0.0025655	0.0025655	0.0025655	0.0025655	0.0025655	0.0616027	0.061	0.096394	0.1632
4 Halogenated Matter (organic)	0	4.32E-10	1.64E-10	8.978E-05	8.978E-05	8.978E-05	8.978E-05	8.978E-05	0.0002718	0.0000028	1.29E-04	
4 Hydrocarbons (unspecified)	0	1.33E-15	2.36E-16	1.60E-12	1.604E-12	1.604E-12	1.604E-12	1.604E-12				
4 Inorganic Dissolved Matter (unspecified)	0	4.63E-09	2.15E-09	1.07E-05	1.071E-05	1.071E-05	1.071E-05	1.071E-05	0.0718143	0.027	5.88E-02	3.74E-05
4 Iron (Fe++, Fe3+)	0								0.4130333		0.394972	
4 Lead (Pb++, Pb4+)	0	4.08E-12	8.95E-13	1.78E-07	1.775E-07	1.775E-07	1.775E-07	1.775E-07	6.264E-07		2.97E-07	
4 Mercury (Hg+, Hg++)	0	1.33E-14	2.36E-15	1.60E-11	1.604E-11	1.604E-11	1.604E-11	1.604E-11				3.90E-08
4 Metals (unspecified)	0	1.52E-17	2.71E-18	1.84E-14	1.845E-14	1.845E-14	1.845E-14	1.845E-14				6.84E-10
4 Nickel (Ni++, Ni3+)	0	1.24E-07	5E-08	2.58E-04	0.0002578	0.0002578	0.0002578	0.0002578	0.3145983	0.002	0.302122	0.000144
4 Nitrate (NO3-)	0	6.63E-15	1.18E-15	8.02E-12	8.022E-12	8.022E-12	8.022E-12	8.022E-12				
4 Nitrogenous Matter (unspecified, as N)	0	6.99E-10	1.45E-10	2.20E-05	2.195E-05	2.195E-05	2.195E-05	2.195E-05	0.0002886	0.00055	8.11E-04	
4 Oils (unspecified)	0	1.79E-13	3.18E-14	2.17E-10	2.166E-10	2.166E-10	2.166E-10	2.166E-10	0.0106078	0.000009	7.81E-03	
4 Organic Dissolved Matter (unspecified)	0	1.19E-06	3.17E-07	0.0018824	0.0018824	0.0018824	0.0018824	0.0018824	0.1090418	0.0027	0.0828252	0.00195
4 Phenol (C6H5OH)	0	2.92E-12	8.2E-13	3.01E-08	3.01E-08	3.01E-08	3.01E-08	3.01E-08	0.0227197	0.000014	1.36E-02	
4 Phosphates (PO4 3-, HPO4--, H2PO4-, H3PO4	0	4.10E-08	7.28E-09	4.96E-05	4.958E-05	4.958E-05	4.958E-05	4.958E-05	0.0009856	0.00018	3.72E-04	
4 Polycyclic Aromatic Hydrocarbons (PAH, unspe	0	6.60E-12	1.17E-12	8.06E-09	8.06E-09	8.06E-09	8.06E-09	8.06E-09		0.0000037		8.61E-05
4 Radioactive Substance (unspecified)	0			1.93E-11	1.925E-11	1.925E-11	1.925E-11	1.925E-11				
4 Salts (unspecified)	0	9.61E-11	1.71E-11	1.16E-07	1.163E-07	1.163E-07	1.163E-07	1.163E-07				
4 Sodium (Na+)	0		3.26E-09	2.22E-05	2.218E-05	2.218E-05	2.218E-05	2.218E-05				
4 Sulfate (SO4--)	0	9.27E-05	0.0000429	0.214176	0.214176	0.214176	0.214176	0.214176	0.0258622		84.7012	
4 Sulfide (S--)	0	1.02E-09	2E-10	2.01E-05	2.01E-05	2.01E-05	2.01E-05	2.01E-05	5.744E-05		5.58E+00	5.00E-04
4 Suspended Matter (unspecified)	0	6.54E-13	1.81E-13	6.34E-09	6.338E-09	6.338E-09	6.338E-09	6.338E-09	0.0049279		1.86E-03	
4 TDS (g)	0	9.67E-06	1.72E-06	0.0117152	0.0117152	0.0117152	0.0117152	0.0117152	0.2464383	0.14	1.74486	0.00015
4 TOC (Total Organic Carbon)	0											
4 Toluene (C6H5CH3)	0	9.94E-12	1.77E-12	1.20E-08	1.203E-08	1.203E-08	1.203E-08	1.203E-08				
4 Water: Chemically Polluted	0	1.46E-13	2.59E-14	1.76E-10	1.765E-10	1.765E-10	1.765E-10	1.765E-10				9.83E-08
4 Zinc (Zn++)	0	1.15E-05	4.86E-06	0.0247683	0.0247683	0.0247683	0.0247683	0.0247683	0.3133333		0.230162	

Appendix D: Life cycle inventory data sources:

1. Fly Ash: No Source
2. Coal Production: Ecobilan's DEAM Database, 2001.
3. Coal Combustion: Ecobilan's DEAM Database, 2001.
4. Sand and Gravel: Based on information from PCA for electricity use and equipment energy use, 2002. This is adjusted with Ecobilan’s DEAM datasets for United States energy production and diesel fuel production data, and NONROAD equipment emissions.
5. Diesel Fuel and Gasoline Production: Ecobilan's DEAM Database, 2001.
6. Rebar Steel and EAF Section Steel: International Iron and Steel Institute, 2000.
7. Electricity: Ecobilan's DEAM Database, 2001.
8. PVA Fiber: Data provided by manufacturer who requested to remain anonymous and from Association of Plastic Manufacturers in Europe (APME) substituted as polyethylene, 1999.
9. Superplasticizer: Modeled as formaldehyde, data from the Association of Plastic Manufacturers in Europe (APME), 1999.
10. Cement: The Portland Cement Association, 2002.
11. Rubber, Wood, and Epoxy: Ecobilan's DEAM Database, 2001.

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