LIFE-CYCLE ASSESSMENT OF HIGHWAY PAVEMENT ALTERNATIVES IN ASPECTS OF ECONOMIC, ENVIRONMENTAL, AND SOCIAL PERFORMANCE

A Thesis

by

ZHUTING MAO

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

MASTER OF SCIENCE

August 2012

Major Subject: Construction Management

Life-Cycle Assessment of Highway Pavement Alternatives in Aspects of Economic, Environmental, and Social Performance

LIFE-CYCLE ASSESSMENT OF HIGHWAY PAVEMENT ALTERNATIVES IN ASPECTS OF ECONOMIC, ENVIRONMENTAL, AND SOCIAL PERFORMANCE

A Thesis

by

ZHUTING MAO

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

MASTER OF SCIENCE

Approved by:

Co-Chairs of Committee,	Kunhee Choi
	Edelmiro Escamilla
Committee Members,	Sarel Lavy-Leibovich
	Ivan Damnjanovic
Head of Department,	Joe Horlen

August 2012

Major Subject: Construction Management

ABSTRACT

Life-Cycle Assessment of Highway Pavement Alternatives in Aspects of Economic,
Environmental, and Social Performance. (August 2012)

Zhuting Mao, B.S., Shanghai Normal University

Co-Chairs of Advisory Committee, Dr. Kunhee Choi
Dr. Edelmiro Escamilla

Economic Input Output Life Cycle Assessment (EIO-LCA) provides economic transactions, environmental emissions, and energy use throughout a product's life cycle based on a dollar amount of the product. A custom EIO-LCA model was conducted to compare three major rigid pavements of Jointed Plain Concrete Pavement (JPCP), Jointed Reinforced Concrete Pavement (JRCP), and Continuously Reinforced Concrete Pavement (CRCP) within the perspective of economic transactions, greenhouse gases, energy use, hazardous waste, toxic releases, water withdrawals, and transportation movements.

The analysis results indicate that CRCP be the most cost-efficient and sustainable choice among the selected rigid pavement alternatives as it requires the lowest life-cycle cost and has the least unfavorable impact on environment when compared to the JPCP and JRCP. Potential improvements could be investigated for the processes of cement manufacturing, power generation and supply, ready-mix concrete manufacturing, and truck transportation because the EIO-LCA results reveal that they are the top sectors contributing to the energy use and greenhouse gases emissions. The results also indicate that some sectors such as storage of materials, landfills, and soil waste management should be taken into account in order to reduce toxic releases. Moreover, the utilization of local human resources as well as raw materials would help to minimize transportation movement.

This study shows that EIO-LCA is a valuable tool and presents how it can help decision-makers make a better-informed decision when there are multiple options. In future studies, uncertainties related to location and time should be captured to generalize the results of the EIO-LCA with more sophisticated data collection and stratification protocol.

DEDICATION

I dedicate this thesis to my wonderful family, especially…

to my mom, Xiaozhen Ye, and my dad, Zhaoyi Mao for opening my eyes to the world;

to my uncle, Xiaoming Ye and Xiaofei Ye, for encouragement and supporting my study;

to my grandparents, Keji Ye, Chengxiang Wang, Shikang Mao, and Huiying Xu for taking care of me;

to my cousin, Hui Liu, for always being an example for me.

ACKNOWLEDGEMENTS

I would like to thank my committee co-chairs, Dr. Kunhee Choi, and Dr. Edelmiro Escamilla, and my committee members, Dr. Sarel Lavy-Leibovich, and Dr. Ivan Damnjanovic, for their guidance and support throughout the course of this research.

Thanks also to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

Finally, thanks to my mother and father for their encouragement and endless love.

NOMENCLATURE

AASHTO	American Association of State Highway and Transportation Officials
AISI	American Iron and Steel Institute
BTS	Bureau of Transportation Statistics
Caltrans	California Department of Transportation
CMU	Carnegie Mellon University
CRCP	Continuously Reinforced Concrete Pavement
CRSI	Concrete Reinforcing Steel Institute
DOT	Departments of Transportation
EA	Environmental Assessments
EIO-LCA	Economic Input-Output Life Cycle Assessment
EIS	Environmental Impact Statements
EO	Executive Order
EPA	Environmental Protection Agency
ESAL	Equivalent Single Axle Loads
FHWA	Federal Highway Administration
GWP	Global Warming Potential
HUD	U.S. Department of Housing and Urban Development

IRF	International Road Federation
ISO	International Organization for Standards
JPCP	Jointed Plain Concrete Pavement
JRCP	Jointed Reinforced Concrete Pavement
LCA	Life Cycle Assessment
LTPP	Long-Term Pavement Performance
NEPA	National Environmental Policy Act
NSF	National Science Foundation
PCC	Portland Cement Concrete
POTW	Publicly Owned Treatment Works
RCRA	Resource Conservation and Recovery Act
SETAC	Society of Environmental Toxicology and Chemistry
SHA	State Highway Agencies
TxDOT	Texas Departments of Transportation
WSDOT	Washington State Department of Transportation

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

1. INTRODUCTION

The United States has nearly 4 million miles (6.5 million kilometers) of highways (FHWA 2006). Roadway pavements in the United States support over 6.17 trillion ton-mile (9 trillion tonne-kilometers) of passengers and freight every year (BTS 2010). Over 400 billion dollars are spent on pavement construction and maintenance worldwide (IRF 2010). Therefore, choosing an appropriate pavement is important.

In the past years, concrete pavements were designed with a life span of 20 to 25 years (Choi 2012). Now many pavements are at the end of their life cycle, and should be rehabilitated. There is a high demand for renewing badly deteriorated pavements. The Federal Highway Administration (FHWA) encourages low-maintenance, long-life concrete pavements whose service life is about 40 years (AISI 2012). Structural design, construction equipment, process technology, and management methods have been researched by state Department of Transportations (DOTs) to achieve a more efficient pavement method.

This thesis follows the style of *Construction Engineering and Management*.

At the same time, the environmental impact of pavements is becoming an issue. Greater attention has been given to sustainable construction based on the fact that pavement construction contributes to a large amount of land, air, and water pollution. Due to such environmental issue, environmental impact assessment is mandated in various countries including the United States.

The National Environmental Policy Act (NEPA) established in 1969 was the first law in the United States for environment enhancement. The most visible NEPA requirement is to ask all federal government agencies to provide Environmental Assessments (EAs) and Environmental Impact Statements (EISs) which contain statements of environmental effects of proposed federal agency actions (Eccleston 2008). Thus, federal government agencies are required to take environmental impact on nature and the community into consideration before undertaking any major federal action. Several DOTs set sustainability as their mission and vision. For instance, Hawaii has a Sustainable DOT-A Program Profile as well as Sustainable High Performance Guidelines (Hawaii DOT 2011). Texas Department of Transportation (TxDOT)'s vision statement includes providing safe, durable, cost-effective, environmentally sensitive, and aesthetic transportation system that work together. Furthermore, in June 2009, a partnership among the Environmental Protection Agency (EPA), the U.S. Department of Housing and Urban Development (HUD), and the U. S. DOT was established to help improve access to affordable housing, more transportation options, and lower transportation costs while protecting the environment in communities nationwide (EPA 2011). In October

2009, President Obama signed Executive Order (EO) 13514 to set sustainability goals for Federal agencies and focus on making improvements in environmental, energy and economic performance. The EO requires federal agencies to reduce greenhouse gas emissions, conserve water, prevent pollution, eliminate waste, and make high performance buildings (Eccleston and March 2011).

Therefore, addressing the sustainability of pavements has become critical for decision makers and policy makers.

2. BACKGROUND

2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) evaluates the product in an environmental view by quantifying its environmental burdens during the entire life-cycle (Joshi 1999). As Figure 1 shows, a life cycle includes products' raw-material extraction, process and manufacture, transportation and distribution, operation and use, and disposal and recycling.

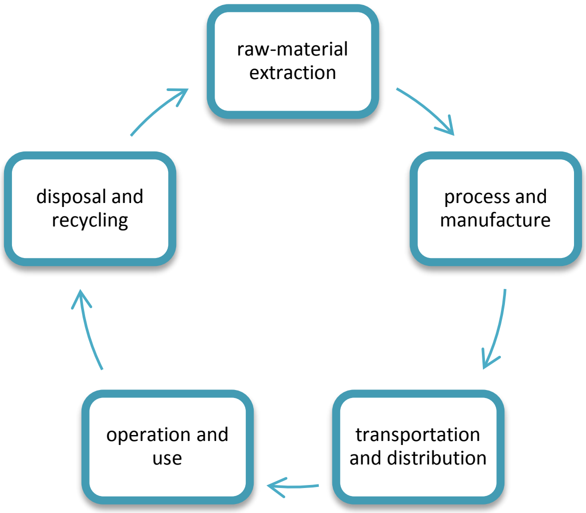


Figure 1. Product Life Cycle

Specifically, a life cycle of pavements can be seen in Figure 2. Pavements start with material extraction and production, and then construction, use, maintenance and rehabilitation, and disposal and recycling. These activities use equipment and transportation, and produce traffic delay and pollutions.

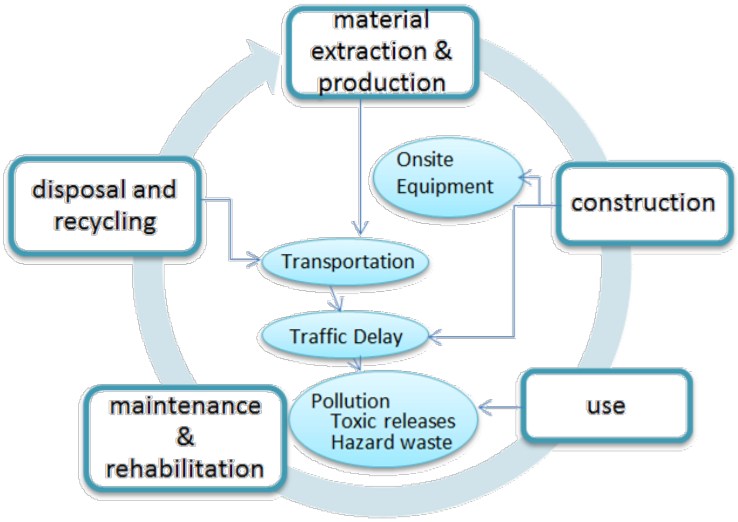


Figure 2. Pavement Life Cycle (adapted from Caltrans 2012)

LCA can be traced back to 1969, when LCA was conducted on beverage containers (Madu 2001). At that time, LCA was used to decide the type of beverage containers that had the least impact on natural resources and the environment. After that, LCA has been broadened to energy supply, demand for fossil, and renewable alternative fuels. Because

LCA considers the entire life cycle of products, it is also known as Cradle-to-Grave Analysis and Life-Cycle Analysis (Ayres et al. 1998).

Two main definitions of LCA are given by the International Organization for Standards (ISO) and the Society of Environmental Toxicology and Chemistry (SETAC).

Defined by the ISO 14040 series (14040 to 14049) in 2006, LCA is “a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle” (EPA 2011).

The definition made by the SETAC in 1993 is “An objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases, to assess the impact of those energy and materials uses and releases to the environment, and to evaluate and implement opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing; transportation; and distribution; use/re-use/maintenance; recycling; and final disposal” (Consoli et al. 1993).

Through compiling the material and resource inputs and environment outputs of a certain product, LCA can evaluate the potential impacts and help inform decision makers. If the most environmentally harmful stage of the product can be identified during LCA analysis, improvements can be made to this specific stage. Thus, raw materials, energy consumption, waste generation, disposal costs, and health risks can be reduced and process efficiency will be improved (ISO 2006). "Based on a survey of LCA, practitioners carried out in 2006 LCA is mostly used to support business strategy (18%) and Research and Development (18%), as input to product or process design (15%), in education (13%) and for labeling or product declarations (11%)"(Cooper and Fava 2006).

There are four phases in LCA shown in Figure 3 (Guinee 2002). They are interdependent to each other.

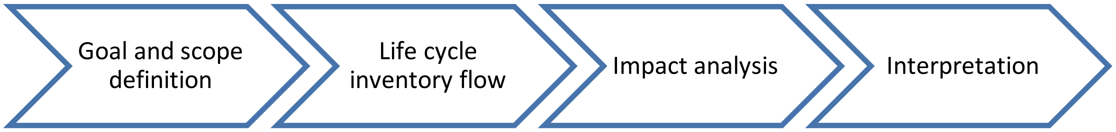


Figure 3. Four Phases in LCA (Guinee 2002)

The first phase, goal and scope definition is critical to the accuracy of LCA. In this phase, the recourse and reference of inputs should be determined as well as the standard of units; system boundaries, assumptions, and limitations should be clearly defined.

In the second phase, life cycle inventory analysis phase, an inventory flow model should be built according to the scope definition. Input flow includes raw materials, energy, and activities in direct and indirect supply chain. Output flow includes releases to air, land, and water. National databases or data sets that come with LCA-practitioner tools, or that can be readily accessed, are the usual sources for information. Care must then be taken to ensure that the secondary data source properly reflects regional or national conditions.

The third phase is impact analysis. Based on life cycle inventory flow, potential impacts will be evaluated. Before evaluation, inventory parameter, impact indicator, and the method of measurement should be selected. Upon the assumptions made in the first phase, normalization, weighting, sorting, and filtering might be used in impact analysis to get a summed impact on the overall environment. However, weighting is not encouraged by the ISO due to its subjectivity (ISO 2006).

The last phase is interpretation. Based on impact analysis, an outcome, conclusion, suggestion and recommendation will be given during the interpretation phase. Attention should be given to the objectivity of interpretation, including sensitivity, consistency, and completeness. The main purpose during interpretation is to draw a conclusion and recommendation at a high confidence level with clear assumptions and limitations stated based on a complete understanding of the development and conduction of LCA.

However, it is almost impossible to meet all the requirements in these phases of LCA with time and financial constraints. First, setting correct boundaries is difficult (Hendrickson et al. 1998). There are direct and indirect interactions during the life cycle, which lead to unclear input parameters for products. For instance, vehicles are made by steel, while steel needs vehicles for distribution. Traditional LCA usually ignores this circularity effect. The only possible way to realistically perform these tasks is to set inputs focused only on the most important process or resources, which might lead to inappropriate decision making. Second, it is hard to ensure the accuracy and currency of the data. Most of the data in previous research is out-of-date and unable to reflect the current impact.

2.2 Economic Input-Output Life Cycle Assessment

To solve the boundary and circularity issues that exist in LCA, Economic Input-Output Life Cycle Assessment (EIO-LCA) was developed by economist Wassily Leontief in the 1930s, causing him to win the Nobel Prize in 1973 (Ochoa et al. 2002). Leontief's model starts with a general model of economy, and can be extended to environmental impacts and energy analysis coupled with supply chain transactions. EIO-LCA divides production into sectors, and builds a general interdependency model to quantify the interrelationships among sectors as shown in Table 1 (Hendrickson et al. 1998).

Table 1. EIO-LCA Sector Model (Hendrickson et al. 1998)

Output from sectors	Input from sectors					O Intermediate output	Y Final demand	X Total output
	1	2	3	…	n			
1	X_{11}	X_{12}	X_{13}	…	X_{1n}	O_1	Y_1	X_1
2	X_{21}	X_{22}	X_{23}	…	X_{2n}	O_2	Y_2	X_2
3	X_{31}	X_{32}	X_{33}	…	X_{3n}	O_3	Y_3	X_3
…	…	…	…	…	…	…	…	…
n	X_{n1}	X_{n2}	X_{n3}	…	X_{nn}	O_n	Y_n	X_n
I Intermediate input	I_1	I_3	I_3	…	I_3			
V Value added	V_1	V_2	V_3	…	V_n		GDP	
X Total input	X_1	X_2	X_3	…	X_n			

Where:

X_{ij}: amount that sector j purchased from sector i

Y_i : final demand for output from sector i

X_i: total output from sector i

$$X_i = Y_i + \sum_j X_{ij}$$

If $A_{ij} = \frac{x_{ij}}{x_j}$

Then

$$X_i = Y_i + \sum_j A_{ij} \cdot X_j$$

In vector notation, it can be displayed like

$$X = Y + AX$$

$$Y = (I - A)X$$

$$X = (I - A)^{-1}Y$$

The variable A indicates the direct requirements of the intersectional relationships. The rows of A show the amount of output from industry i required to produce one dollar of output from industry j.

Thus, total production X from each sector can be calculated by knowing final demand of each sector Y and the normalized input-output matrix A (Hendrickson et al. 2005).

In the mid-1990s, based on Leontief model, the Green Design Institute at Carnegie Mellon University (CMU) designed EIO-LCA online software to estimate the resources and energy required for products as well as environmental emissions resulting from products (CMU 2011). The output from EIO-LCA on-line software provides the relative impacts of various products, services, and material use.

EIO-LCA models consist of national economic input-output models, including publicly available resource use and emissions data. By choosing only one sector category, monetary value of the products, and effects to display, one can get the analysis results immediately. These EIO-LCA models can be applied to different national economies including the United States, Canada, Germany, Spain, and China. Two states, Pennsylvania and West Virginia have their own models in state level (CMU 2011). EIO-LCA online software has been accessed more than one million times and has been used for economic models in the United States, Canada, Germany, Spain, and China (CMU 2011).

3. RESEARCH SCOPE

3.1 Problem Statement

Concrete is one of the most widely used materials in highway construction because of its superior fire resistance, extremely long life span, and low transportation cost. Between 21 to 31 billion tons of concrete is consumed every year in the world (Sathiyakumari 2010). According to FHWA, 40% interstates and 36% freeways and expressways are using rigid pavements in urban areas across the United States (FHWA 1998). Most research focus on the comparison between asphalt and concrete pavements (Berthiaume and Bouchard 1999; Horvath and Hendrickson 1998a; Roudebush 1999; Zapata and Gambatese 2005). It is observed that there is no systematic research with the goal of investigating highway rehabilitation alternatives among rigid pavements such as Jointed Plain Concrete Pavement (JPCP), Jointed Reinforced Concrete Pavement (JRCP), and Continuously Reinforced Concrete Pavement (CRCP) from the perspective of LCA.

This study focuses on the economic and environmental impacts of these three major rigid pavement alternatives by using EIO-LCA in order to provide guidelines and recommendations for rigid pavements.

Moreover, aging of the transportation infrastructure in the United States has caused numerous pavement rehabilitation projects. EIO-LCA analysis will help State Highway Agencies (SHAs) to make better decisions on choosing economical and sustainable pavements. Without sustainable development, future generations might face resource shortages, and a polluted and uncomfortable environment.

However, most of the previous research on comparing materials of pavements by using process-based LCA and EIO-LCA were conducted before 2000 (Berthiaume and Bouchard 1999; Horvath and Hendrickson 1998a; Roudebush 1999). In addition to the fact that there has been very little done specifically aiming at investigating rigid-type pavement alternatives, the data used in these studies become obsolete. One of goals of the study is to validate the results of previous research studies by using the latest EIO-LCA model, recently created by the Green Design Institute at CMU.

3.2 Research Objectives

To address the issues stated earlier, the main objective of this study is to investigate pavement alternatives that use Portland Cement Concrete (PCC), with the primary focus on JPCP, JRCP, and CRCP from the perspective of LCA. This addresses the National Science Foundation (NSF)'s goal of "reducing adverse human impact on resource use; the design and synthesis of new materials with environmentally benign impacts; and maximizing the efficient use of individual materials throughout their life cycles (NSF 2004)".

The study has the following two particular objectives:

1. To evaluate and quantify the economic, environmental, and social impacts of JPCP, CRCP, and JPCP;
2. To provide guidelines and recommendations based on findings and conclusions.

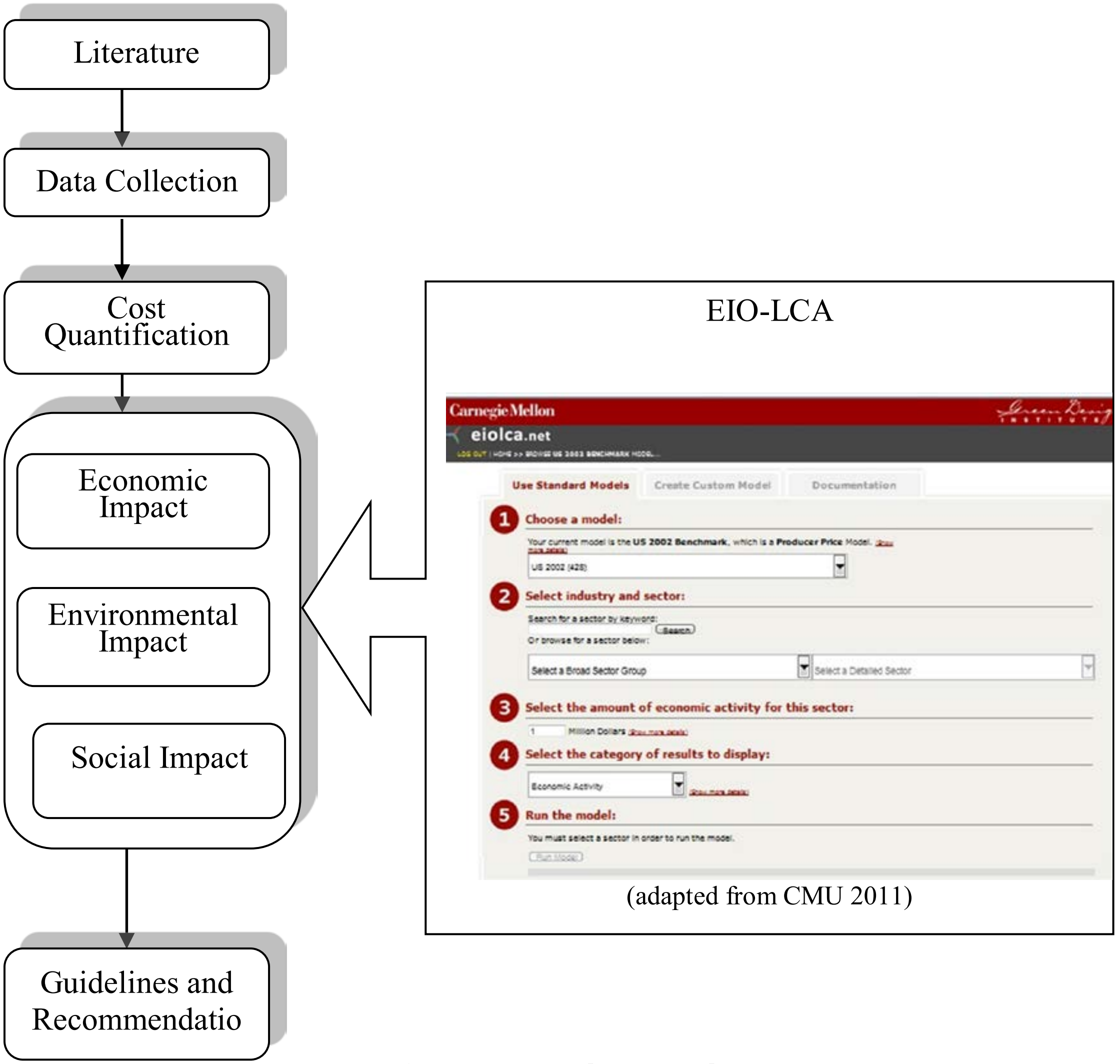
Critically, the study results will provide to state DOTs and SHAs a general view of the environmental effects on JPCP, CRCP, and JPCP in their life cycles and to help them to make better-informed decisions.

3.3 Research Significance

This study is expected to be a significant leap over previous studies that focus heavily on the economic, environmental, and social impacts on highway rigid pavements. The same framework can be applied for different types of pavements or other products when the environmental and cost efficiency are considered.

3.4. Research Approach

In order to conduct comprehensive research on JPCP, CRCP, and JPCP from the perspective of LCA, the proposed research approach includes literature review, data collection, economic-environmental-and-social impact analysis, and recommendations and guidelines. The research approach is shown in Figure 4.



1 Choose a model:

Your current model is the **US 2002 Benchmark**, which is a **Producer Price** Model.

US 2002 (428)

2 Select industry and sector:

Search for a sector by keyword:

Or browse for a sector below:

Select a Broad Sector Group

Select a Detailed Sector

3 Select the amount of economic activity for this sector:

1 Million Dollars

4 Select the category of results to display:

Economic Activity

5 Run the model:

You must select a sector in order to run the model.

(adapted from CMU 2011)

Figure 4. Research Approach

3.5 Assumption and Limitation

The standard EIO-LCA models are based on several assumptions (CMU 2012). First, the models used for EIO-LCA apply to a single nation's economies. Second, the prices of products sold to other sectors are the same. Third, imports have the same production characteristics as comparable products made in the country of interest. That means the environmental effect of the production of a truck imported and used by the United States is comparable to the truck made in the United States. Fourth, the data used in each EIO-LCA model represent the year of the model. The uncertainty of inflation and changes over time needs to be taken into consideration. Fifth, the data of each model are obtained from the public resources and surveys. The error in the original data was treated as part of uncertainty.

Based on these assumptions, this study is limited by the accuracy of the estimation for each pavement. Only the most critical sectors, ready-mix concrete, and iron and steel mills manufacturing, were used for the inputs of EIO-LCA model due to the limited reliable data. If more data highly contributed to the production of rigid pavement (truck transportation, wholesale trade, management of companies and enterprises, sand, gravel, clay, and refractory mining, architectural and engineering services, stone mining and quarrying, and oil and gas extraction) can be investigated, the results will be more accurate.

In addition, the conclusions are based on typical interstate rigid pavements and the assumption that when pavement alternatives are exposed to the same conditions they will have the same general behavior. Each project will have its own unique circumstance and requirement, the inputs and outputs may vary.

4. LITERATURE REVIEW

Research findings and conclusions about JPCP, CRCP, and JPCP with respect to design, application, performance, materials, and maintenance and relevant studies on LCA, EIO-LCA are summarized and evaluated in this section.

4.1 Rigid Pavements Facts

Most rigid pavements are made with PCC. PCC can mainly be divided into three different types such as JPCP, JRCP, and CRCP.

4.1.1 Jointed Plain Concrete Pavement

JPCP is the most commonly used pavement alternative among the existing rigid pavement alternatives. The JPCP has been used in 43 states across the nation with a well-established design procedure (WSDOT 2011). JPCP is to last 20 to 40 years depending on the design requirements and traffic volumes (WSDOT 2011).

JPCP uses both transverse and longitudinal contraction joints for crack control as shown in Figure 5. The distance between two joints, mainly depending on slab thickness, usually is between 12 feet (3.7 meters) and 20 feet (6.1 meters) space without reinforcing steels (WSDOT 2011). Load is transferred by dowel bars transversely and by tie bars longitudinally. If there is a crack at middle of a slab, only aggregate interlock transfers load across the joint.

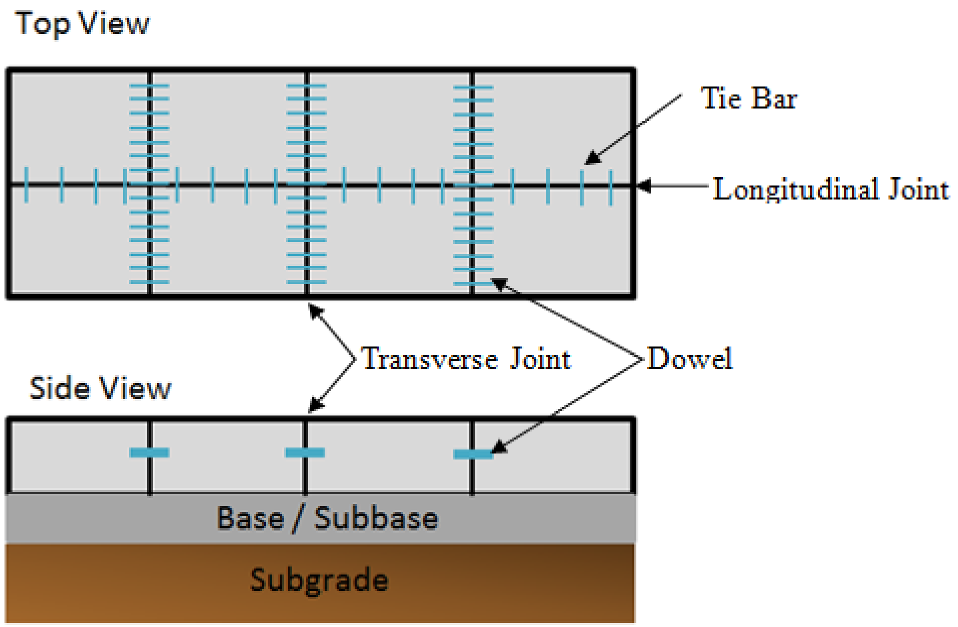


Figure 5. Cross-section of JPCP (WSDOT 2011)

4.1.2 Jointed Reinforced Concrete Pavement

JRCP uses both contraction joints and reinforcing steel (AASHTO 1993). Maximum 49 feet (15 meters) is allowed between joints (WSDOT 2011). Reinforcing bars or a thick wire mesh need to be used for holding cracks tightly together. Load is transferred by dowel bars transversely and by reinforcing steel or wire mesh across cracks. Transverse joint distance ranges from 25 feet (7.6 meters) to 50 feet (15.2 meters) (WSDOT 2011).

About 9 states have JRCP design procedures, although JRCP is just a small portion among their pavement (WSDOT 2011).

Figure 6 illustrates a typical JRCP's section view.

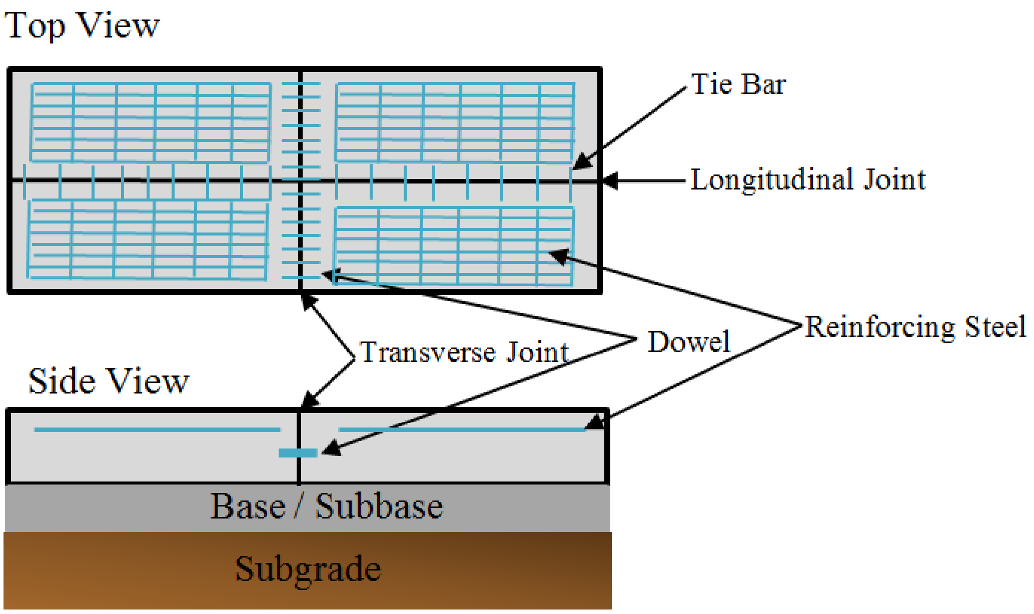


Figure 6. Cross-section of JRCP (WSDOT 2011)

4.1.3 Continuously Reinforced Concrete Pavement

Approximately 75 years ago, CRCP started to be used in the United States (AISI 2012). According to California Highway Design Manual, CRCP is more cost effective in terms of high volume pavements because there are no sawn transverse joints which lead to its long-term performance and reduced maintenance (Caltrans 2006). CRCP is commonly used for Interstate System in Illinois, Texas, and North Dakota (WSDOT 2011).

As shown in Figure 7, CRCP uses only continuous reinforcing steel, so only longitudinal joints are required. Around 0.7 percent of the cross-sectional pavement is steel (ASSHTO 1993); less steel may apply in warmer area. Cracks within 0.02 inch (0.5 millimeter) are allowed, and the continuous reinforcement can tightly hold the cracks together (ASSHTO 1993). Loads are transferred from slab to slab by aggregate interlock, so no contraction joint is needed. CRCP is prestressed concrete pavement, which can resist greater loads and using smaller cross-section area and longer spans. CRCP can be applied to both wet and dry conditions due to less water penetration.

CRCP is considered as a desirable pavement type, especially for high-speed roadways where heavy traffic volumes are carried out (Caltrans 2011). CRCP has a more durable and safer performance. A 20-year research of in-service pavements across North America by the Long-Term Pavement Performance (LTPP) program concluded that CRCP maintains its original, smooth surface and offer comfort ride experience to road users over time (AISI 2012). Since there are no transverse joints and tighter transverse cracks with CRCP, it has a smoother surface and enables better vehicle fuel efficiency. CRCP requires less maintenance, thus maintenance cost and time associated with maintaining traffic control, employing road repair crews, and purchasing repair materials can be reduced. There will be less traffic delays and disruptions with fewer reconstruction or repairs. Moreover, CRCP offers a perfect support for future potential overlays. Overlays can tight and bridge cracks easily, which extends the serve life of CRCP.

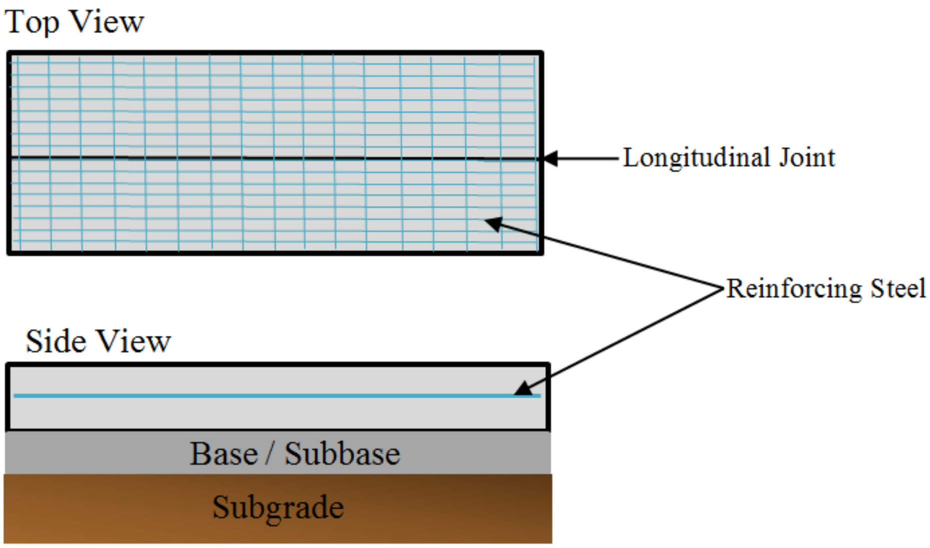


Figure 7. Cross-section of CRCP (WSDOT 2011)

Not all the states in the United States have realized the benefits of CRCP. Six states such as Illinois, Texas, Oklahoma, Oregon, South Dakota, and Virginia are the major states that adopt the CRCP. Some other states use CRCP for experiments. For example, California Department of Transportation (Caltrans) only uses CRCP for the projects whose traffic index is less than 11.5 or in High Mountain and High Desert climate regions to test its performance (Caltrans 2011).

However, CRCP may not be desirable for light-traffic areas, such as parking lots. If there are utilities under the pavement, CRCP will be damaged when accessing the utilities underneath the roadbed (Delatte 2008).

4.2 Previous Studies on Pavement Alternatives Using LCA

Horvath conducted several research studies comparing asphalt pavements with reinforced concrete pavements in terms of environmental impact. In his study, it was concluded that asphalt is more environmentally friendly in manufacturing while concrete is more eco-friendly during use. For girders, concrete is exceling in manufacturing and use, whereas steel is superior in recycling (Horvath 1997). In another research, by using LCA Inventory analysis based on available data, Horvath found that asphalt pavements seem to be more sustainable because they have lower ore and fertilizer input requirements, lower toxic emissions, and have a higher rate of recycling, which makes the fact that asphalt pavements have been used more often reasonable (Horvath and Hendrickson 1998a). The limitation of both research studies is the uncertainty of the data used. In addition, many other crucial environmental factors including dust emissions, water usage, and waste generation were not considered in these analyses.

Another study conducted by Horvath was the LCA inventory analysis application on steel and steel-reinforced concrete bridges (Horvath and Hendrickson 1998b). The conclusion was that steel-reinforced concrete bridges have more favorable environmental impacts in overall than steel bridges while steel might be better when considering the recycling and reusing. However, the results appear to be skewed due to the lack of data and acceptable metric standards.

LCA was conducted for a comparative study that compared asphalt and PCC in another study (Zapata and Gambatese 2005). It showed that asphalt uses less energy during the extraction, manufacturing, and transportation phases and asphalt can be recycled more often than concrete and steel.

Muga et al. (2009) compared economic and environmental impacts of JPCP and CRCP with different percentages of slag and fly ash by LCA. The study found that CRCP costs 46% more than JPCP during the construction, but JPCP costs 80% more than CRCP to maintain the pavement over 35 years. JPCP has around 40% more emissions than CRCP for all mix types.

The LCA and EIO-LCA were compared in several studies. Graham J. Treloar found the disadvantages of traditional LCA, including its time-consuming nature and high cost to perform. Moreover, it can only be reliable during the design process. Graham suggested a hybrid life-cycle inventory to fill the gaps which are not considered in traditional LCA, such as maintenance, replacement, and operation (Treloar et al. 2004).

Table 2 summarized the difference between LCA and EIO-LCA. LCA uses inventory analysis and get the results for a specific product. During the data collection, different units for each element might be different. In LCA, the interactions and circularity between each element are ignored. For EIO-LCA, it considers the interactions and circularity and can be apply to a general product. All the inventory will be converted to U.S. dollar amount during the data collection.

Table 2. Comparison of Conventional LCA and EIO-LCA

LCA	EIO-LCA
Ignoring circularity during the transaction	Considering circularity during the transaction
Analysis represents a specific product	Analysis represents a general product
Different unit	Uniform unit: dollar amount

5. DATA COLLECTION

During data collection, general and average data about pavement sectors were collected from official and reliable resources including the American Association of State Highway and Transportation Officials (AASHTO), RS Means, and construction price index.

5.1 Pavement Design

In order to perform an unbiased analysis, an equivalent cross-section design of typical JPCP, JRCP, and CRCP was considered. For this study, the design of each pavement type was carefully carried out to reflect the typical cross-sections of the three selected alternatives. In order for the designs to have the same service life, performance, and functions, it was assumed that a major interstate highway was planned to be built in urban area. The highway would be 3,280 feet (1 kilometer) long, and 48 feet (14.8 meters) wide (2 lanes in each direction, and each lane is 12 feet (3.7 meters) wide). There would be 1900 single unit trucks per day, 1750 double unit trucks per day, and 250 truck trains per day. In the design lane 80% of the loading would occur. The annual growth of the traffic volume is estimated to be 2%. The PCC elastic modules (E_c) would be 31,026 Megapascals (4,500,000 pounds per square inch) and the modules of rupture ($S_c^{'}$) of PCC would be 5.17 Megapascals (750 pounds per square inch). The pavement would sit on a cement-treated soil subbase whose effective dynamic k-value is 250 pounds per square inch. The pavement is designed to serve for 40 years. The serviceability index would drop from 4.2, the initial design serviceability index, to 1.5, the terminal serviceability index. A reliability of 95% and a 0.4 combined standard error would be considered (AASHTO 1993).

The design of rigid pavements based on these assumptions strictly followed the 1993 AASHTO Guide for Design of Pavement Structures (AASHTO 1993).

AASHTO 1993 empirical equations were used to determine the thickness. This empirical equation comes from all of the AASHTO rigid roads data. The road test lasted two years of the pavement life, so environmental factors can hardly be taken into consideration. The equation is:

$$\log_{10}(W_{18}) = Z_R \times S_0 + 7.35 \times \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.5-1.5}\right)}{1+\frac{1.624\times 10^{7}}{(D+1)^{8.46}}} + (4.22 - 0.32p_t) \times \log_{10}\left[\frac{(S_c')(C_d)(D^{0.75}-1.132)}{215.63(J)\left(D^{0.75}-\frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}}\right)}\right]$$

Where:

W$_{18}$: predicted number of 18,000 pounds (80 kiloNewtons) Equivalent Single Axle Loads (ESALs)

W_{18} shows traffic loads during the road service life. ESAL can be calculated from historical data of different type of vehicles. A single unit truck counts 0.34 ESALs, a double unit truck counts 1.0 ESALs, and a truck train counts 2.6 ESALs.

Z_R: standard normal deviate

Standard normal deviance is a value coming from the standard normal probability table (z-table) for checking confidence interval. If the possibility that the pavement can meet the design performance is 95%, the confidence interval is 95% and the corresponding Z value in the z-table is -1.645 (See Appendix A).

Table 3 shows the suggested Z_R for various functional classifications

Table 3. Z_R Table (AASHTO 1993)

Functional Classification	**Confidence Interval**	
	Urban	**Rural**
Interstate and Other Freeways	85 – 99.9	80 – 99.9
Principal Arterials	80 – 99	75 – 95
Collectors	80 – 95	75 – 95
Local	50 – 80	50 – 80

S_o: combined standard error of the traffic prediction and performance prediction

S_o is a value defining how widely the input value will change because of the uncertainty due to the long time period, population growth, climate changes, and other anticipated reasons. Typical values of S_o used are 0.40 to 0.50 for flexible pavements and 0.35 to 0.40 for rigid pavements.

D: slab depth or thickness

p_t: initial design serviceability index

p_t ranges from 4.0 to 5.0 depending on quality and smoothness of projects. 5.0 is the highest score in serviceability index, which represents a perfect pavement. The default p_t is 4.2, the immediately-after-construction value

p_0: terminal serviceability index

p_o ranges from 1.5 to 3.0 based on the usage of roads. The default p_o is 1.5, the bottom line of the end-of-life value.

ΔPSI: difference between p_0 and p_t

Basically, $p_{t,}$ $p_{0,}$ and ΔPSI are the indicators of the pavement performance.

S_c': modules of rupture of PCC

C_d: drainage coefficient

Table 4 shows the C_d vale according to the quantity of drainage. The default C_d is 1.00.

Table 4. C_d Table (AASHTO 1993)

Quantity of drainage		Percentage of time pavement structure is exposed to moisture levels approaching saturation			
Rating	**Water removed within**	**< 1%**	**1% - 5%**	**5% - 25%**	**> 25%**
Excellent	2 hours	1.25 – 1.20	1.20 – 1.15	1.15 – 1.10	1.10
Good	1 day	1.20 – 1.15	1.15 – 1.10	1.10 – 1.00	1.00
Fair	1 week	1.15 – 1.10	1.10 – 1.00	1.00 – 0.90	0.90
Poor	1 month	1.10 – 1.00	1.00 – 0.90	0.90 – 0.80	0.80
Very poor	Never drain	1.00 – 0.90	0.90 – 0.80	0.80 – 0.70	0.70

J: load transfer coefficient

J defines the distribution of load across the joints or cracks, which has a significant influence in road performance. It is the percentage of approach slab deflection over leave slab deflection. The J value for JPCP, JRCP, and CRCP is listed in table 5.

Table 5. J Table (AASHTO 1993)

	J			
Type of shoulder	Asphalt		Tied PCC	
Load transfer devices	Yes	No	Yes	No
JPCP & JRCP	3.2	3.8 – 4.4	2.5 – 3.1	3.6 – 4.2
CRCP	2.9	N/A	2.3 – 2.9	N/A

E_c: Elastic modulus of PCC

If there is not enough strength data available, E_c can be assumed as 27,500 Megapascals (4,000,000 pounds per square inch), which corresponds to a compressive strength of 34.5 Megapascals (5000 pounds per square inch).

K: modulus of subgrade reaction

K estimates the support of the layer underneath surface layer. Usually, it ranges from 13.5 Megapascals (50 pounds per square inch) for weak support, to 270 Megapascals (1000 pounds per square inch) for strong support.

According to the design assumptions, the following numbers were quantified and summarized in Table 6.

Table 6. Pavement Design Parameters

Varible	Value	Detail
$\mathbf{W_{18}}$	54,326,933 ESALs	Single unit trucks ESALs/year = 1900 truck/day × 0.8 × 365 day × 0.34 ESAL/truck = 188,632 ESALs/year Double unit trucks ESALs/year = 511,000 ESALs/year Truck trains ESALs/year = 189,800 ESALs/year Total ESALs/year = 188,632 ESALs/year + 511,000 ESALs/year + 189,800 ESALs/year = 889,432 ESALs/year Total ESALs for 40 years = $\mathbf{899,423}\left[\frac{(\mathbf{1+0.02})^{\mathbf{40}}\mathbf{-1}}{\mathbf{0.02}}\right]$ = 54,326,933 ESALs
Z_R	-1.645	z-value for 95% confidence interval is -1.645 (Check Appendix 1)
S_o	0.4	
p_t	4.2	
P_o	1.5	
ΔPSI	2.7	4.2 - 1.5 =2.7
$\mathbf{S_c'}$	750 psi	
$\mathbf{C_d}$	1.0	
J	2.8 for JPCP&JRCP 2.6 for CRCP	Use the average value
$\mathbf{E_c}$	4,500,000 psi	
K	250 psi	

The values shown in Table 6 were then incorporated into the AASHTO empirical equation. The thickness of typical cross-sections for JPCP and JRCP was calculated to be 11.105 inches (28 centimeters).

$$\log_{10}(54,326,933) = -1.645 \times 0.4 + 7.35 \times \log_{10}(D+1) - 0.06$$

$$+ \frac{\log_{10}(\frac{2.7}{4.5-1.5})}{1+\frac{1.624\times 10^{7}}{(D+1)^{8.46}}} + (4.22 - 0.32 \times 4.2)$$

$$\times \log_{10}\left[\frac{(750)(1.0)(D^{0.75}-1.132)}{215.63(2.8)(D^{0.75}-\frac{18.42}{(\frac{4,500,000}{250})^{0.25}})}\right]$$

D = 11.105 inches

The thickness of CRCP was 10.625 inches (27 centimeters)

$$\log_{10}(54,326,933) = -1.645 \times 0.4 + 7.35 \times \log_{10}(D+1) - 0.06$$

$$+ \frac{\log_{10}(\frac{2.7}{4.5-1.5})}{1+\frac{1.624\times 10^{7}}{(D+1)^{8.46}}} + (4.22 - 0.32 \times 4.2)$$

$$\times \log_{10}\left[\frac{(750)(1.0)(D^{0.75}-1.132)}{215.63(2.6)(D^{0.75}-\frac{18.42}{(\frac{4,500,000}{250})^{0.25}})}\right]$$

D = 10.605 inches

The slab thickness needs to be rounded to the nearest 0.5 inch, so the slab thickness was 11.5 inches (29.21 centimeters) for JPCP and JRCP, and 11 inches (27.94 centimeters) for CRCP.

5.2 Quantity Takeoff

5.2.1. Quantity Takeoff for JPCP

JPCP uses only tie bars as transverse joints, and dowels as longitudinal joints. For an 11.5 inch-thick (29.21 centimeters) JPCP, the space between transverse joints was 15 feet (4.572 meters). No.9 bars of 18 inches (45.72 centimeters) long at 12 inches (30.48 centimeters) intervals were used as dowels. No.6 bars of 50 inches (127 centimeters) long at 36 inches (91.44 centimeters) intervals were used as tie bars. For a 3,280 feet (1 kilometer) long, 48 feet (14.6meter) wide pavement, there were 10,464 No.9 bars of 18 inches (45.72 centimeters), and 3279 No.6 bars of 50 in (127 centimeters).

Total volume of JPCP pavement: 3,280’ × 48’ × 11.5’’ = 150,880 cu·ft

Concrete weight: 150 lb/cu·ft (2400 kg/m^3)

Table 7 shows the quantity takeoff for JPCP.

Table 7. Quantity Takeoff for JPCP

Elements	**Spacing**	Number	Length	Volume	Weight
Concrete				150,880 – 109 – 41.94 = **150,729 cu·ft**	150,729 cu·ft × 150 lb/cu·ft = **22,609,350 lb**
Dowels	#9 (18'' long) @ 12''	10,464	18'' × 10,464 = 188,352'' = **15,696 ft**	1 sq·in × 188,352'' = 188,352 cu·in = **109.00 cu·ft**	15,696 ft × 3.400 lb/ft = **53,366 lb**
Tie bars	#6 (50'' long) @ 36''	3,279	50'' × 3,279 = 163,950'' = **13,663 ft**	0.442 sq·in × 163,950''= 72,466 cu·in = **41.94 cu·ft**	13,663 ft × 1.502 lb/ft = **20,522 lb**

5.2.2. Quantity Takeoff for JRCP

JRCP uses not only transverse joints and longitudinal joints but also reinforcing bars or wire mesh. Reinforcing bars was used in this study. For 11.5 inches-thick (29.21 centimeters) JRCP, the space between transverse joints was 40 feet (12 meters). No.4 bars of 18 inches (45.72 centimeters) at 24 inches (60.96 centimeters) were needed as dowels. No.4 bars of 50 inches (1.27 meter) at 24 inches (60.96 centimeters) were needed to be used as tie bars. No.4 bars at 24 inches (60.96 centimeters) were used as transverse reinforcing steels and No.4 bars at 12 inches (30.48 centimeters) were used as longitudinal reinforcing steels. For a 3,280 feet (1 kilometer) long and 48 feet (14.6meters) wide pavement, there were 1,863 No.4 bars of 18 inches (45.72 centimeters), 4,920 No.4 bars of 36 inches (91.44 centimeters), and 74,464 feet of No.4 reinforcing steel bars.

Total volume of JRCP pavement: 3,280’ × 48’ × 11.5’’ = 150,880 cu·ft

Concrete weight: 150 lb/cu·ft (2400 kg/m^3)

Table 8 shows the quantity takeoff for JRCP.

Table 8. Quantity Takeoff for JRCP

Elements	**Spacing**	Number	Length	Volume	Weight
Concrete				150,880 – 3.80 – 13.39 – 107 – 214 = **150,542 cu·ft**	150,542 cu·ft × 150 lb/cu·ft = **22,581,300 lb**
Dowels	#4 (18’’ long) @ 24’’	1,863	18’’ × 1,863 = 33,534’’ = **2,795 ft**	0.196 sq·in × 33,534’’ = 6,573 cu·in = **3.80 cu·ft**	2,795 ft × 0.668 lb/ft = **1,867 lb**

Table 8. Continued

Elements	**Spacing**	Number	Length	Volume	Weight
Tie bars	#4 (24'' long) @ 36''	4,920	24'' × 4,920 = 118,080'' = **9,840 ft**	0.196 sq·in × 118,080'' = 23,144 cu·in = **13.39 cu·ft**	9,840 ft × 0.668 lb/ft = **6,573 lb**
Transverse reinforcing steel	#4 @ 24''	3,280'/ 24'' = **1,640**	1,640 × 48' = **78,720 ft**	0.196 sq·in × 78,720' × 12 = 185,149 cu·in = **107 cu·ft**	78,720 ft × 0.668 lb/ft = **52,585 lb**
Longitudinal reinforcing steel	#4 @ 12''	48' / 12'' = **48**	48 × 3,280' = **157,440 ft**	0.196 sq·in × 157,440' × 12 = 370,299 cu·in = **214 cu·ft**	157,440 ft × 0.668 lb/ft = **105,170 lb**

5.2.3. Quantity Takeoff for CRCP

CRCP uses only reinforcing bars. For an 11 inch-thick (27.94 centimeters) CRCP, No.5 bars at 48 inches (1.22 meters) were used as transverse reinforcing steels and No.6 bars at 24 inches (60.96 centimeters) were used as longitudinal reinforcing steels. For the planned pavement, there are 1,863 No.4 bars of 18 inches (45.72 centimeters), 4,920 No.4 bars of 36 inches (91.44 centimeters), and 74,464 feet of No.4 reinforcing steel bars.

Total volume of JRCP pavement: 3,280' × 48' × 11'' = 144,320 cu·ft

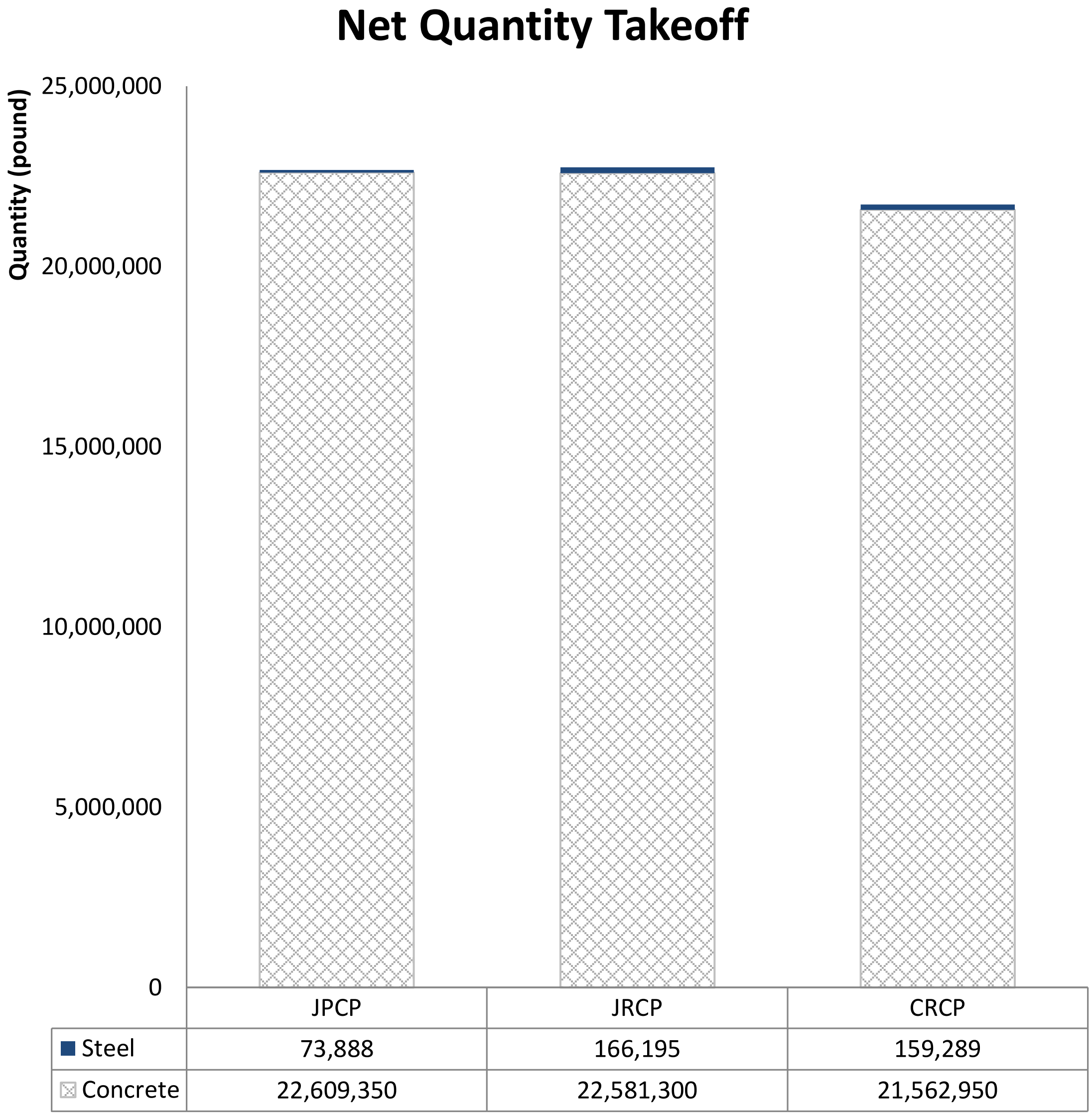
Concrete weight: 150 lb/cu·ft (2400 kg/m^3)

Table 9 shows the quantity takeoff for CRCP.

Table 9. Quantity Take off for CRCP

Elements	**Spacing**	Number	Length	Volume	Weight
Concrete				144,320 – 84 – 483 = **143,753 cu·ft**	143,753 cu·ft × 150 lb/cu·ft = **21,562,950 lb**
Transverse reinforcing steel	#5 @ 48’’	3,280’/ 48’’ = **820**	820 X 48’ = **39,360 ft**	0.307 sq·in × 39,360’ × 12 = 145,002 cu·in = **84 cu·ft**	39,360 ft × 1.043 lb/ft = **41,052 lb**
Longitudinal reinforcing steel	#6 @ 24’’	48’ / 24’’ = **24**	24 × 3,280’ = **78,720 ft**	0.442 sq·in × 78,720’ × 12 = 398,638 cu·in = **231 cu·ft**	78,720 ft × 1.502 lb/ft = **118,237 lb**

The concrete and steel quantities for the three rigid pavements were summarized in Figure 8.



	JPCP	JRCP	CRCP
■ Steel	73,888	166,195	159,289
☒ Concrete	22,609,350	22,581,300	21,562,950

Figure 8. Concrete and Steel Quantity for JPCP, JRCP, and CRCP

5.3 Cost Estimation for Life-Cycle Assessment

For the unit cost determination of the selected three pavements, 2011 Heavy Construction Cost Data from RS Means was used for cost calculation. The cost data are sourced from manufacturers, dealers, distributors, and contractors all cross the United States and Canada, and included10% waste. The following unit costs in Table 10 were used in this study.

Table 10. RS Means Unite Cost (RS Means 2011)

Line number	**Description**	**Unit**	**Bare material ($)**	**Total Cost including Overhead& Profit ($)**
03 31 05.35 0350	Normal weight concrete, ready mix, delivered includeds local aggregate, sand, Portland cement, and water, excludeds all additives and treatments 4500psi	C.Y.	91.50	101
03 21 10.50 2550	Reinforcing Steel, Mill Base Plus Extras #4	Ton	72	79
03 21 10.50 2600	Reinforcing Steel, Mill Base Plus Extras #5	Ton	36	39.5
03 21 10.50 2650	Reinforcing Steel, Mill Base Plus Extras #6	Ton	32.5	35.5
03 21 10.50 2700	Reinforcing Steel, Mill Base Plus Extras #7 to #11	Ton	43	47.5

Based on RS Means cost data, the total price (Quantity × Unit Price) was computed for concrete and steel for the JPCP, JRCP, and CRCP, detailed below:

JPCP

Concrete: 150,729 cu•ft × (1+10%) × $101/C.Y. = $ 620,222

Steel: 53,366 lb × (1+10%) × $47.5/ton + 20,522 lb × (1+10%) X $35.5/ton = $ 1,795

JRCP

Concrete: 150,542 cu•ft × (1+10%) × $101/C.Y. = $ 629,452

Steel: (1,867 lb. + 6,573 lb. + 52,584 lb. + 105,170 lb.) × (1+10%) × $79/ton = $ 3,311

CRCP

Concrete: 143,753 cu•ft × (1+10%) × $101/C.Y. = $ 591,517

Steel: 41,052 lb X (1+10%) × $39.5/ton + 118,237 lb × (1+10%) × $35.5/ton = $ 3,200

6. DATA ANALYSIS

EIO-LCA and SimaPro are two commonly used software programs for conducting an LCA analysis. The LCA was completed by using EIO-LCA (www.eiolca.net), because the EIO-LCA is based on the United States data. SimaPro utilizes European data which might be not applicable to this study when considering the scope of the study.

6.1 Model Selection

There are thirteen standard models available for the EIO-LCA; they can be simplified to producer models and purchaser models according to the analysis boundary. Producer price models refer to the boundary including the impact associated with all processes from resource extraction to product assembly (CMU 2011). All processes after the production site are not included. In purchaser price models, however, distribution the product to the final consumer is also included (CMU 2011). Six models are US nation-wide; three models are for Pennsylvania, West Virginia, and the combination of both. Four international models exist for Germany, Spain, Canada, and China. Each model is for a different year and each area has a different sector number ranging from 58 to 491. In this study, the US national purchaser price model in 2002 was selected as the standard model.

However, the standard model can only be used for generic scenarios. In this study the standard model was used to analyze pavement constructions. When different pavement types need to be investigated, a custom model or a hybrid model must be used.

A custom model can be used to develop a hypothetic product with a direct purchasing demand for multiple direct sectors. In contrast, a hybrid model allows the possibility of adjusting the purchasing demand with sectors across entire economic sectors (CMU 2011). Based on this study, three hybrid models based on the US national purchaser price model in 2002 were established.

In the EIO-LCA chosen as the major analysis tool for this study, the “Construction” sector was selected as the primary sector on top of the “Other Nonresidential Structures” sub-sector because these sectors include highway, street, and bridge construction, which is the main focus of this study. In the LCA analysis utilizing EIO-LCA, the direct economic monetary values for the selected three pavement alternatives were then input to analyze how these two main sectors are interrelated to other sectors in order to examine the economic, environmental, and social implications.

Figure 9 shows the inputs and outputs of the EIO-LCA model used in this study.

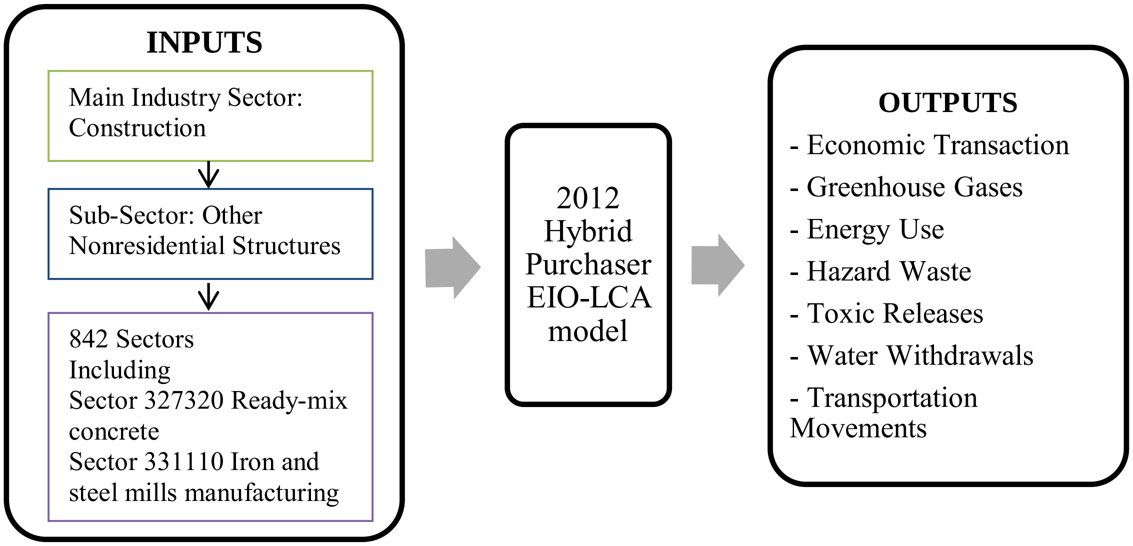


Figure 9. Main Framework of EIO-LCA Model for This Study

6.2 Data Adjustment

Because the selected standard model uses 2002 data and the cost estimation was based on 2011 RS Means database, inflation or deflation over the nine year span should be reflected to use a year-of-expenditure dollar. The construction price index (See Table 11) was used to convert 2011 dollar value to 2002. The 2002 price index for highway construction is 53.1 and the 2011 index is 84 (Caltrans 2012). The 2011 value (V_{2011}) can be converted to 2002 value (V_{2002}) by applying a time adjustment factor: $V_{2002} = V_{2011} \times \frac{53.1}{84}$.

Table 11. Price Index for Highway Construction

Year	Price Index for Highway Construction
2002	53.1
2003	56.6
2004	79.1
2005	98.1
2006	104.1
2007	100
2008	95
2009	78.4
2010	76.8
2011	84

Table 12 shows the changed inputs of Sector 327320 Ready-mix concrete and Sector 331110 Iron and steel mills manufacturing for JPCP, JRCP, and CRCP hybrid models:

Table 12. Input Values for Concrete and Steel Sectors

Inputs	JPCP	JRCP	CRCP
Concrete	$ 392,067	$ 397,904	$ 373,923
Steel	$ 1,135	$ 2,093	$ 2,023

The other sectors' value in the model will be adjusted automatically according to these inputs.

6.3 Outputs

Using the EIO-LCA tool, a LCA analysis was performed to investigate the impacts of the selected highway pavement alternatives from the seven perspectives:

- Economic Transaction
- Greenhouse Gases
- Energy Use
- Hazard Waste
- Toxic Releases
- Water Withdrawals
- Transportation Movements

Under each category, the total value of each parameter and component value was assigned to each industry sector. After sorting, filtering, and comparing the data, the three pavements' economic and environmental impacts were compared. There was also ample data to support the underlying reasons behind the discovered results.

6.3.1 Economic Transaction

In the economic activity, "Economic transaction cost" in millions of dollars represents the complete economic supply chain of purchases needed to yield the product.

The top ten sectors of all three pavements in economic activity were the same, and included: Other Nonresidential Structures, ready-mix concrete manufacturing, cement manufacturing, truck transportation, wholesale trade, management of companies and enterprises, sand, gravel, clay, and refractory mining, architectural and engineering services, stone mining and quarrying, and oil and gas extraction.

Figure 10 shows that CRCP had the least total economic transaction and direct economic transaction amount, followed by JPCP, and JRCP. These conclusions were reasonable as CRCP uses the least amount of materials. When the design requirements are the same, CRCP is less thick than JPCP and JRCP. Thus, the quantity of cement of CRCP is much less than that of JPCP and JRCP. In addition, the application of CRCP shows it requires very little maintenance cost because of its durable and stable performance (CRSI 2012; Muga et al. 2009).

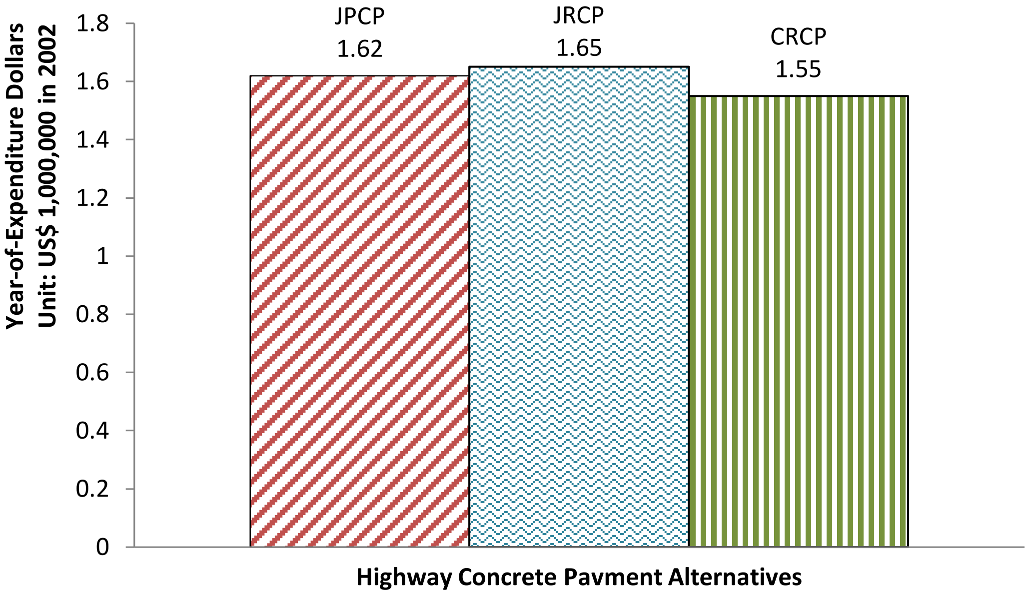


Figure 10. Economic Impact: Economic Transaction Cost

6.3.2 Greenhouse Gases

Global Warming Potential (GWP) measures how much heat greenhouse gases trap in the atmosphere (Shine et al. 2005). The unit of GWP is metric tons of carbon dioxide (CO_2) equivalent emissions (t CO_2). GWP is composed of CO_2 Fossil, CO_2 process, Methane (CH_4), Nitrox dioxide (N_2O), and other high-GWP gases. CO_2 Fossil, and CO_2 process represents the emissions of CO_2 into the air from each sector from fossil fuel combustion sources, and sources other than fossil fuel combustion.

In rigid pavements, cement manufacturing produced around 50% t CO_2e of the total GWP, followed by power generation and supply, read-mix concrete manufacturing, truck transportation, oil and gas extraction, sand, gravel, clay, and refractory mining, petroleum refineries, and other basic organic chemical manufacturing.

From Figures 11, 12, and 13, CRCP had 5% less greenhouse emissions than JRCP, and 4% less than JPCP. The biggest difference between three rigid pavements was CH_4, and CO_2 fossil. Also, CH_4, and CO_2 fossil were the two largest components among greenhouse gas emissions. Fossil fuels produce more than 90% of greenhouse gas emissions in the United States due to people's reliance on cars for transportation (EPA 2011). In this study, fossil fuels were mainly produced by cement manufacturing's chemical reactions, coal mining, and solid waste. CH_4 resulted from the transport and production of coal, natural gas, and oil. The least variance between pavement types was HFC/PFCs and N_2O emissions. HFC/PFCs were mainly produced by refrigeration and air-conditioning equipment. N_2O came from agricultural soil management, animal manure, mobile combustion, nitric acid production, and stationary combustion.

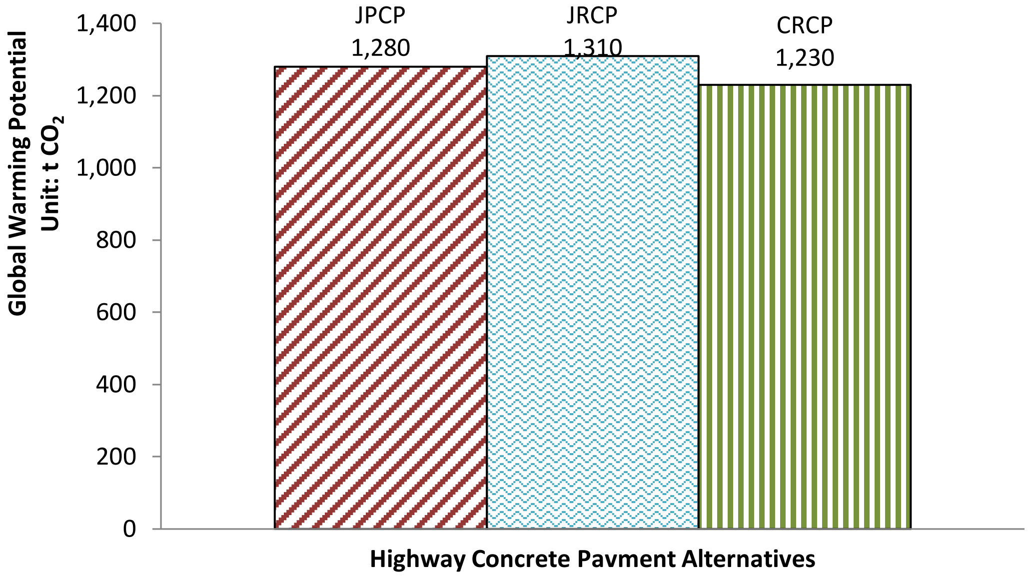


Figure 11. Environmental Impact: Global Warming Potential

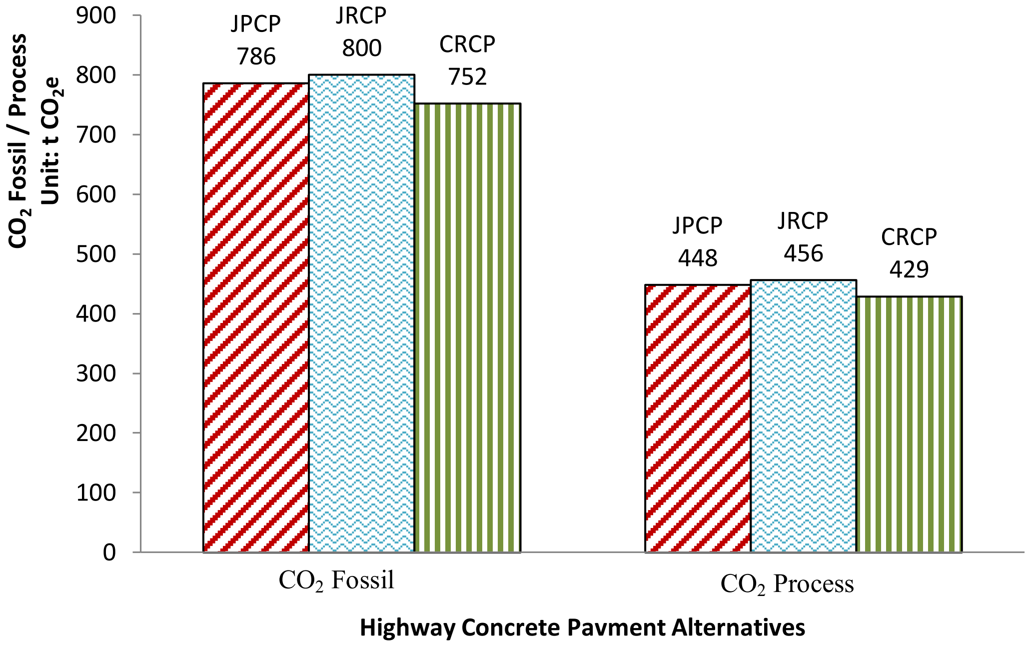


Figure 12. Environmental Impact: CO_2 Emissions

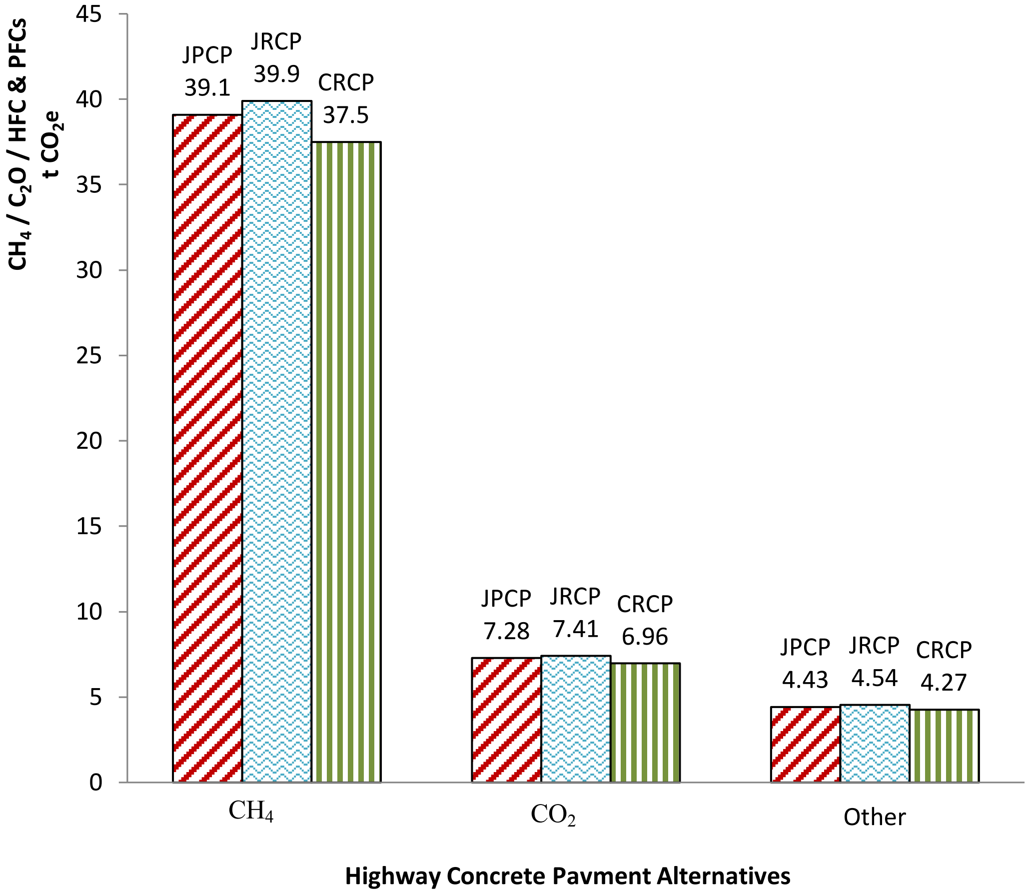


Figure 13. Environmental Impact: Other Greenhouse Gases Emissions

6.3.3 Energy Use

Total energy used was measured in Terajoules (TJ). Total energy use was calculated from all fuels and electricity including coal, natural gas, petroleum-based fuel, biomass/waste fuel, and 31% of non-fossil fuel electricity. If all electricity is calculated, the fuel used to make the electricity will be double counted. Thus 31% of the electricity that comes from non-fossil sources was used.

Under the category of energy, cement manufacturing, power generation and supply, and ready-mix concrete manufacturing were the top three consumers. Other energy consumption was mainly from truck transportation, sand, gravel, clay, and refractory mining, petroleum refineries, organic chemical manufacturing, stone mining and quarrying, and oil and gas extraction.

Figure 14 illustrates the total energy consumption for three rigid pavements, and Figure 15 shows the energy use in more detail.

Overall, CRCP was the most energy-friendly choice because it used 5.6% less energy than JRCP, and 3.8% less energy than JPCP. Among all the energy consumers, the amount of coal used between the three pavements reflected the largest difference.

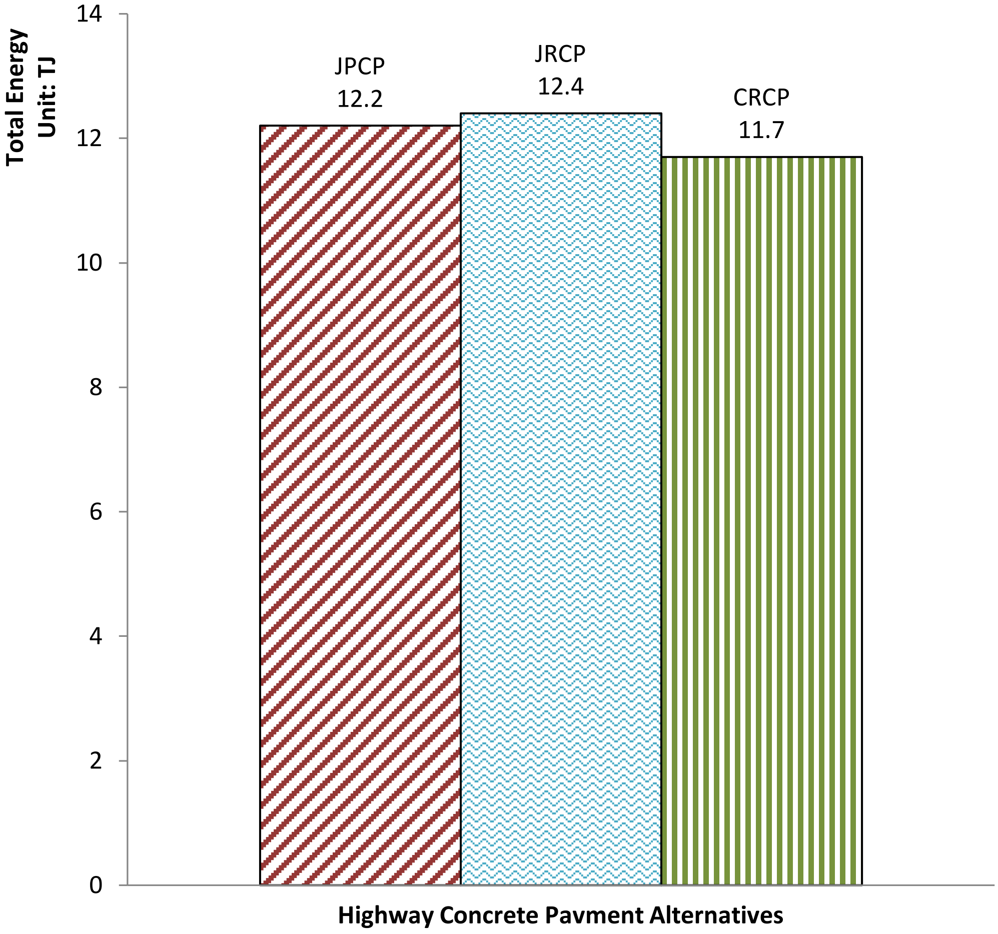


Figure 14. Environmental Impact: Total Energy Use

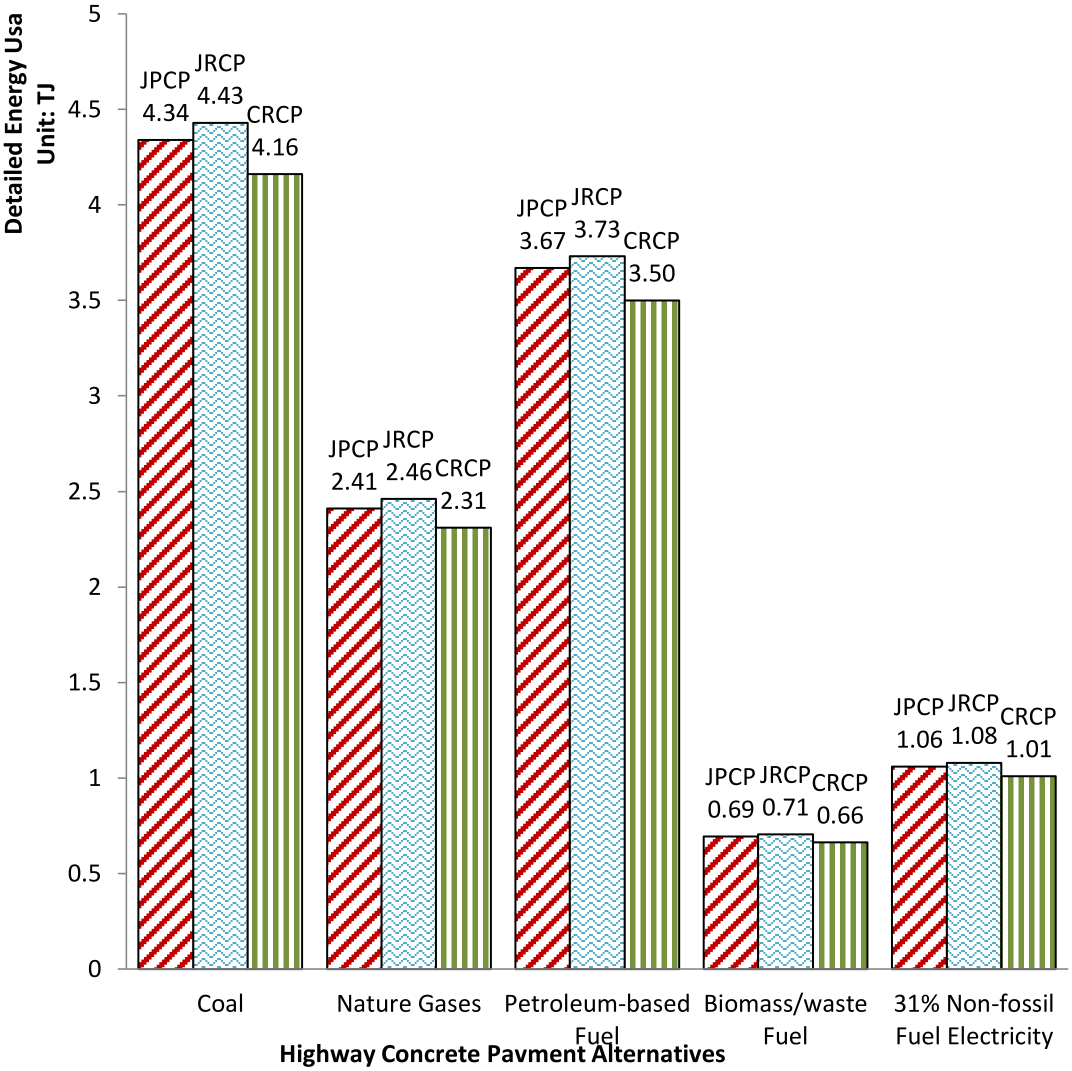


Figure 15. Environmental Impact: Detailed Energy Use

6.3.4 Hazardous Waste

Hazardous waste is identified by the Resource Conservation and Recovery Act (RCRA), was made by the US EPA (EPA, 2011). This Act seeks to assure that hazardous waste is properly managed. The EPA manages which substances are required to be reported in response to the RCRA. These hazardous wastes are potentially harmful not only to the health of human beings but also to the environment. They can be in any form and at any stage of products. The universal hazardous wastes are lithium or lead containing batteries, fluorescent light bulbs, and products containing mercury (EPA 2011). In this study, organic chemical manufacturing, petroleum refineries, and plastics material and resin manufacturing were the top three sectors that contributed to RCRA Hazardous Waste, followed by waste management and remediation services, basic inorganic chemical manufacturing, iron and steel mills, wholesale trade, semiconductor and related device manufacturing, and coating, engraving, heat treating and allied activities.

As shown in Figure 16, JRCP had the largest amount RCRA hazardous waste, followed by JPCP and CRCP.

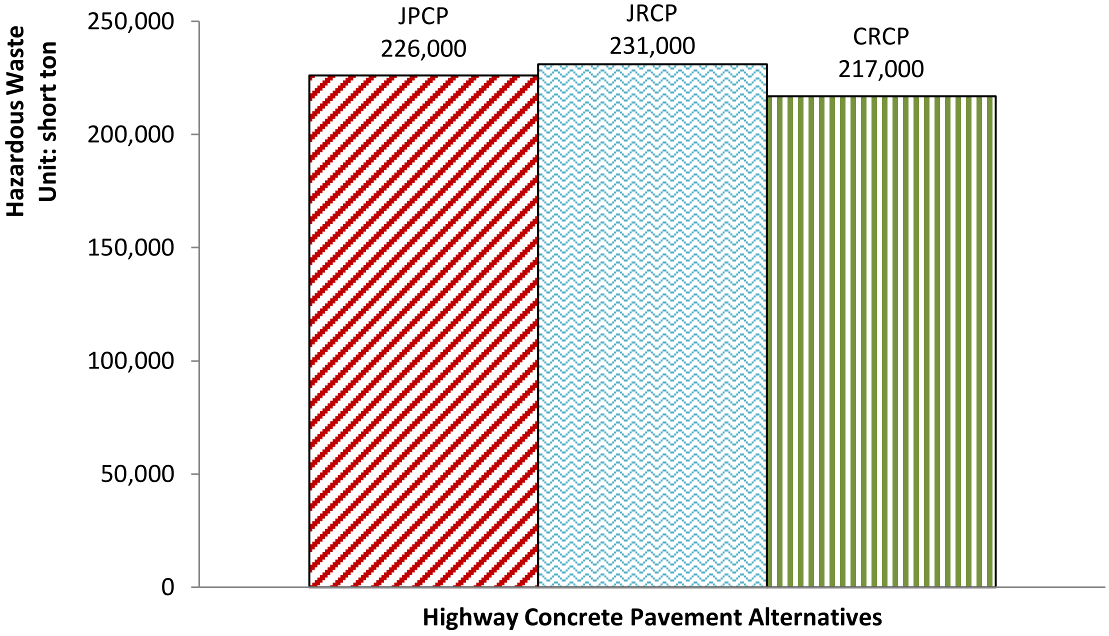


Figure 16. Environmental Impact: Hazardous Waste

6.3.5 Toxic Releases

Toxic release in the EIO-LCA model summarizes toxic emissions by aggregating across all toxic substances regardless of impact (CMU 2011). The toxic emissions are divided by the release resources, including fugitive air releases, point air releases, surface water releases, underground water releases, land releases, offsite releases, metal Publicly Owned Treatment Works (POTWs), and nonmetal POTWs. Fugitive air is defined as the air released from unconfined air streams, such as equipment leaks, ventilation systems, evaporative losses from surface impoundments and spills (CMU 2011). Point air releases occur from confined air streams including stacks, vents, ducts or pipes. Discharges to rivers, lakes, oceans and other bodies of water are cauterized to water releases. They can be divided into surface water releases and underground water releases. Land releases are composed of on-site waste buried in landfills, soil wastes. Offsite releases include all the transactions of chemical shipments off-site with the purpose of disposal, recycling, combustion for energy recovery or treatment.

In this rigid pavement study, toxic releases came from organic chemical manufacturing, petroleum refineries, plastics pipe and pipe fitting manufacturing, plastics material and resin manufacturing, alumina refining and primary aluminum production, paperboard mills, cement manufacturing, and fertilizer manufacturing.

As shown in Figure 17, among all toxic releases, point air and land toxic releases were six to ten times greater than the other toxic releases.

While the outputs offered some detailed information, the EIO-LCA website admits that it is not a very good way of summarizing the impact of toxins (CMU 2011).

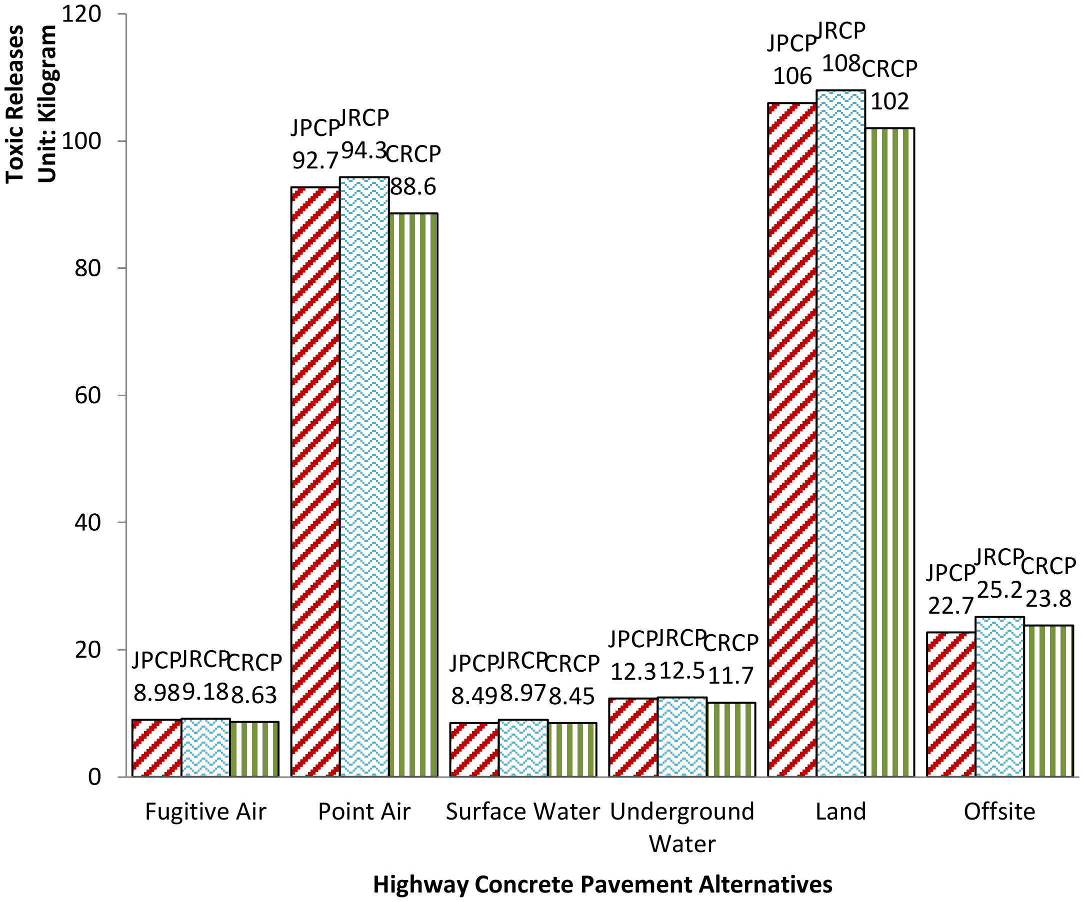


Figure 17. Environmental Impact: Toxic Releases

6.3.6 Water Withdrawals

Water withdrawals is the process of diverting water from a surface water or groundwater source. It can be measured by thousands of gallons (kGal).

Power generation and supply, sand, gravel, clay, and refractory mining, stone mining and quarrying, grain farming, and paint and coating manufacturing used more than 50% of water for rigid pavements. Other water withdrawals came from organic chemical manufacturing, paperboard mills, crop farming, cotton faming, and ready-mix concrete manufacturing.

According Figure 18, CRCP withdrew the least water. JRCP and JPCP used 6.4% and 3.6% more water than that which was used in CRCP.

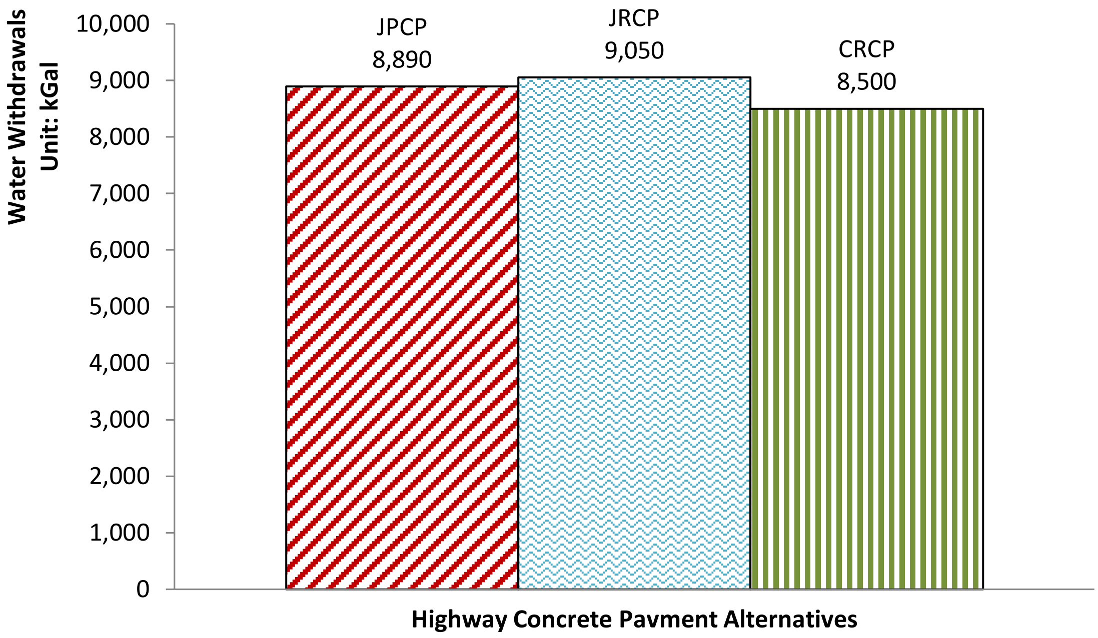


Figure 18. Environmental Impact: Water Withdrawals

6.3.7 Transportation Movements

Total movements are comprised of the movements in a ton-kilometer (ton-km), where one ton-km indicates one ton being moved one kilometer in distance. Movements can be divided into eight modes: by air, oil pipe, gas pipe, rail, truck, water, international air, and international water.

The top ten sectors under transportation were ready-mix concrete manufacturing, organic chemical manufacturing, leather and allied product manufacturing, alkalis and chlorine manufacturing, chemical product and preparation manufacturing, leather and hide tanning and finishing, cement manufacturing, paint and coating manufacturing, printing, and communication and energy wire and cable manufacturing.

International water is any water transcending international boundaries. As shown in Figures 19 and 20, the transportation movement via international waters was more than half of the total transportation movements. JRCP had the most transportation movement, and CRCP had the least.

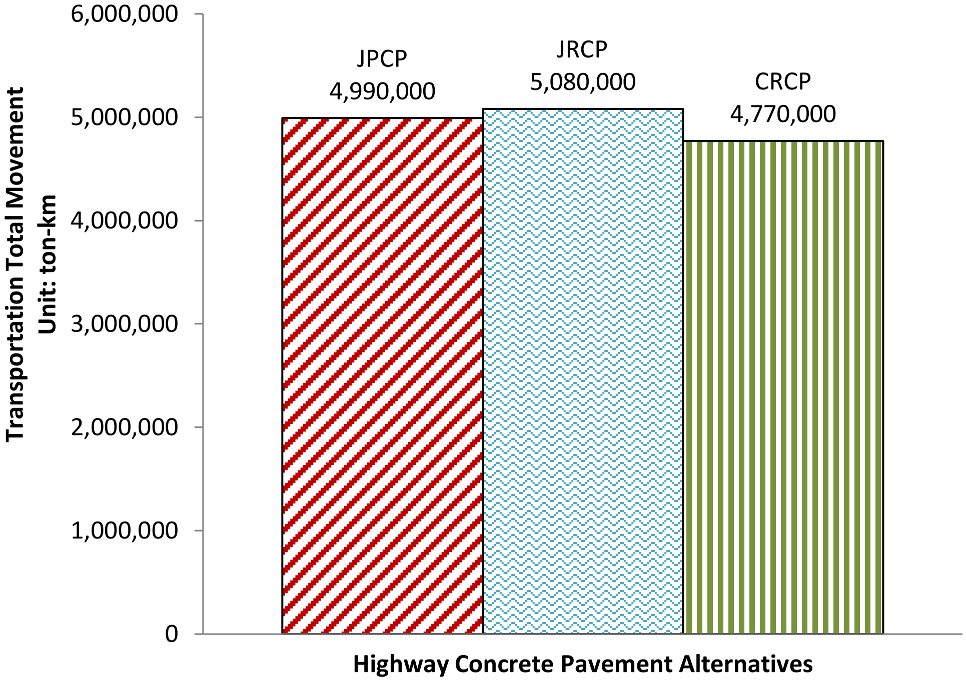


Figure 19. Social Impact: Total Transportation Movement

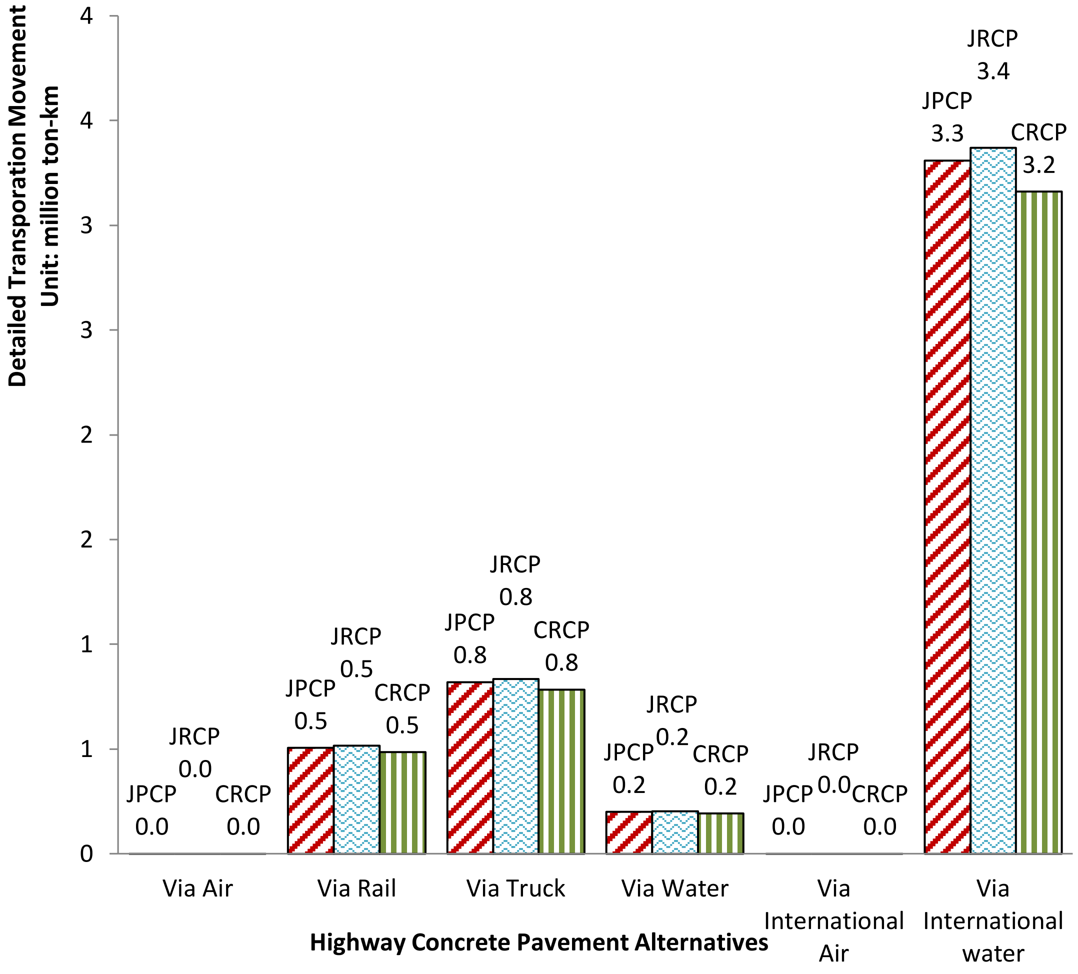


Figure 20. Social Impact: Detailed Transportation Movement

6.4 Output Summary

From the outputs, CRCP had the least cost and environmental impacts among all environmental categories during its life cycle, while JRCP had the most. The main reason for these results is that CRCP is thinner while the other design requirements are the same.

CRCP is a sustainable choice as it has the least life cycle cost and emissions. This result corresponds with previous research showing that CRCP is more environmental friendly (Muga et al., 2009; CRSI 2012) and economical over its life time (CRSI 2012) when compared to other rigid pavements.

7. CONCLUSION

As a result of the demand for replacing highway pavements in light of a deteriorating environment, EIO-LCA has been used to investigate the economic and environmental impact of three major rigid pavements, JPCP, JRCP, and CRCP, for highway construction.

This study has shown how EIO-LCA can be conducted for decision-makers when there are multiple possibilities of rigid pavements. An equivalent design for an interstate highway has been conducted for the three selected pavements according to the ASSHTO pavement design guild. Based on the design, quantity of concrete and steel was calculated and then converted to dollar amount through RS Means data. Before inputting these values into the custom EIO-LCA model based on the 2002 US national purchaser price model, the cost values were adjusted to 2002 by applying the construction price index.

The findings from the outputs are summarized as follows:

- CRCP is the most cost-efficient and environmentally-friendly pavement strategy when compared to JPCP and JRCP. It is because CRCP consumes around less cement compared to other rigid pavement alternatives when the design requirements are comparable. With the lowest cement use, CRCP has the least amount of greenhouse emissions, energy use, RCRA hazardous waste, toxic releases, water withdrawals, and transportation movements.

- Cement is a major consumer of raw materials, emitter of greenhouse gases and contributor to water and air pollution in rigid pavements. Cement manufacturing is the top sector of economic activity in rigid pavements, and it contributes more than half t CO_2e of the total GWP. Within the industry of cement manufacturing, the top consumers of energy use were coals and petroleum-based fuel.

- Power generation and supply, ready-mix concrete manufacturing, and truck transportation produce a large portion of greenhouse gases, especially CH4 and CO2.

- For rigid pavements, the toxic releases are mainly from point air and land releases. The proper management of storage, landfills, and soil waste can significantly reduce the toxic releases.

- The most frequent means of movement is via international water for ready-mix concrete manufacturing. Thus, local materials and manufacturing is encouraged to be utilized.

- EIO-LCA is a valuable tool to provide quick and broad results regarding economic transaction and sustainability. It reduces the circularity and boundary issues seen in traditional LCA. A hybrid or custom model is able to improve the accuracy and reduce the error of the model.

Although CRCP is an economical and sustainable choice among the rigid pavements, in practice, more factors will be considered when a pavement decision needs to be made. For instance, the factors of climate, soil and foundation type, traffic loading, and design requirements all need to be taken into consideration.

Moreover, the results from this study were based on the average data across the United States according to the EIO-LCA data resources. Considering the characteristics of different project circumstances, the regional differences in EIO-LCA need to be developed at the more detailed levels of states and cities.

For future research in perspectives of sustainability, similar studies could be conducted for different types of pavements with alternative materials, not limited to but including fly ash, and slag (Bilodeau and Malhotra 2000; Naik et al. 1995) to achieve a more sustainable goal.

REFERENCES

AASHTO (American Association of State Highway and Transportation Officials). (1993). *AASHTO guide for design of pavement structures 1993*, AASHTO, Washington, DC.

AISI (American Iron and Steel Institute). (2012). "Continuously reinforced concrete pavement: roads for this generation and the next." *AISI*, <http://www.steel.org/en/The%20New%20Steel/~/media/Files/SMDI/Construction/CRCP%20-%20Marketing%20-%20CRCP%20Brochure.ashx> (Apr.8, 2012).

Ayres, R. U., Ayres, L. W., and Martinas, K. (1998). "Exergy, waste accounting, and life-cycle analysis." *Energy*, 23(5), 355-363.

Berthiaume, R., and Bouchard, C. (1999). "Exergy analysis of the environmental impact of paving material manufacture." *Transactions of the Canadian Society for Mechanical Engineering*, 23(1B), 187–96.

Bilodeau, A. and Malhotra, V.M. (2000). "High-volume fly ash system: concrete solution for sustainable development.", *Materials Journal*, 97(1), 41-48.

BTS (Bureau of Transportation Statistics). (2010). *National transportation statistics*. BTS, Washington, DC.

Caltrans (California Department of Transportation). (2006). "Highway design manual." *Caltrans*, <http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm > (Dec.11, 2011).

Caltrans (California Department of Transportation). (2011) "Construction analysis for pavement rehabilitation strategies Caltrans 'rapid rehab' software." *Caltrans*, <http://www.dot.ca.gov/research/roadway/ca4prs/index.htm > (Dec.1, 2011).

Caltrans (California Department of Transportation). (2012). "Price index for selected highway construction items." *Caltrans*, <http://www.dot.ca.gov/hq/esc/oe/contract_progress/cost-index-summary.pdf> (May 7, 2012).

Choi, K., Kwak, Y.H. (2012). "Decision-support model for incentives/disincentives time-cost tradeoff." *International Journal of Automation in Construction*, 21 (1), 219-228.

CMU (Carnegie Mellon University). (2011). "EIO-LCA: free, fast, easy life cycle assessment." *CMU,* <http://webcache.googleusercontent.com/search?q=cache:r12BHSa_RQEJ:www.eiolca.net/+eio+lca&cd=1&hl=en&ct=clnk&gl=us> (Dec.2, 2011).

CMU (Carnegie Mellon University). (2012). "Assumptions, uncertainty, and other considerations with the EIO-LCA method." *CMU,* <http://www.eiolca.net/Method/assumptions-and-uncertainty.html> (Apr.22, 2012).

Consoli, F., Allen, D., and Bousted, I. (1993). Guidelines for life-cycle assessment: a code of practice, *Society of Environmental Toxicology and Chemistry*, Pensacola, FL.

Cooper, J.S., and Fava, J. (2006). “Life cycle assessment practitioner survey: summary of results.” *Journal of Industrial Ecology*, 10 (4), 12-14.

CRSI (Concrete Reinforcing Steel Institute). (2012). “Paving the prairie states: CRCP’s success in North and South Dakota.” *Concrete Reinforcing Steel Institute,* <http://www.conveyinc.com/things/crsi58.pdf> (Apr.10, 2012).

Delatte, N. (2008). *Concrete pavement design, construction, and performance*, Taylor and Francis, London.

Eccleston, C.H. (2008). *NEPA and environmental planning: tools, techniques, and approaches for practitioners*. CRC Press, Boca Raton, FL.

Eccleston, C. H., and March F. (2011). *Global environmental policy concepts, principles, and practice*, CRC Press, Boca Raton, FL.

EPA (Environmental Protection Agency). (2011). “Defining life cycle assessment.” *EPA*, <http://www.gdrc.org/uem/lca/lca-define.html> (Nov.24.2011).

FHWA (Federal Highway Administration). (1998). *Life cycle cost analysis in pavement design demonstration project 115 –participant handbook*, FHWA, Washington, DC.

FHWA (Federal Highway Administration). (2006). *Highway statistics 2005*. FHWA, Washington, DC.

Guinee, J. B. (2002). "Handbook on life cycle assessment operational guide to the ISO standards." *The International Journal of Life Cycle Assessment*, 7(5), 311-313.

Hawaii DOT (Hawaii Department of Transportation). (2011). "Sustainable DOT-A." *Hawaii Department of Transportation*, <http://hawaii.gov/dot/airports/doing-business/sustainabledota> (Nov.27 2011).

Hendrickson, C. T., Horvath, A. Joshi, S. and Lave, L. (1998). "Economic input-output models for environmental life-cycle assessment." *Environmental Science and Technology*, 32(7), 184–191.

Hendrickson, C. T., Lave, L. B., and Matthews, H. S. (2005). *Environmental life cycle assessment of goods and services: an input-output approach*, Resources for the Future Press. Earthscan, London.

Horvath A. (1997), "Estimation of environmental implications of construction materials and designs using life cycle assessment techniques", PhD Dissertation, Dept. Of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA.

Horvath, A., and Hendrickson, C. (1998a). "Comparison of environmental implications of asphalt and steel-reinforced concrete pavements." *Transportation Research Record: Journal of the Transportation Research Board*, 1626 (13), 105-113.

Horvath, A., and Hendrickson, C. (1998b). “Steel vs. steel-reinforced concrete bridges: environmental assessment.” *Journal of Infrastructure System*, 4(3), 111–117.

IRF (International Road Federation). (2010). *World road statistics 2010,* IRF, Geneva, Switzerland.

ISO (International Organization for Standards). (2006), *Environmental management – Life cycle assessment – requirements and guidelines*, ISO, Geneva, Switzerland.

Joshi, S. (1999). “Product environmental life-cycle assessment using input-output techniques.” *Journal of Industrial Ecology*, 3(2-3), 95-120.

Madu, C. N. (2001). *Handbook of environmentally conscious manufacturing*, Kluwer, Boston, MA.

Muga, H.E., Mukherjee, A., Mihelcic, J.R., and Kueber, M.J. (2009). “An integrated assessment of continuously reinforced and jointed plane concrete pavements.” *Journal of Engineering Design Technology.* 7, 81–98.

Naik, T.R., Ramme, B.W. and Tews, J.H. (1995), “Pavement construction with high-volume class C and class F fly ash concrete.” *Materials Journal*, 92 (2), 200-210.

NSF (National Science Foundation). (2004). “Materials use: science, engineering, and society.” *National Science Foundation*, <http://www.eng.nsf.gov/be/muses/> (Dec.2 2011).

Ochoa, L., Hendrickson, C., Matthews, H. S. (2002). "Economic input-output life-cycle assessment of US residential buildings." *Journal of infrastructure systems*, 8(4), 132-139.

Roudebush, W. H. (1999). *Environmental value engineering assessment of concrete and asphalt pavement*, Portland Cement Association, Skokie, IL.

RS Means. (2011). *Heavy construction cost data*, RS Means, Kingston, MA.

Sathiyakumari, K. (2010). "A tree based model for high performance concrete mix design," *International Journal of Engineering Science and Technology*, 2(9), 4640-4646.

Shine, K. P., Fuglestvedt, J. S., Hailemariam, K., and Stuber, N. (2005). "Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases." *Climate Change*, 68(3), 281–302.

Treloar, G.J., Love, P.D., and Crawford, R.H. (2004). "Hybrid life-cycle inventory for road construction and use." *Journal of Construction Engineering and Management*, 130 (1), 43–49.

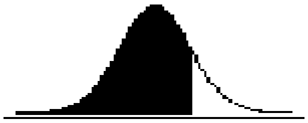
WSDOT (Washington State Department of Transportation). (2011). "WSDOT pavement guide." *WSDOT*, <http://training.ce.washington.edu/wsdot/> (Nov.24 2011).

Zapata, P. and Gambatese, J.A. (2005). “Energy consumption of asphalt and reinforced concrete pavement materials and construction.” *Journal of Infrastructure Systems*, 11(1), 9–20.

APPENDIX A

Standard Normal Probability table (z-Table)

The table shows the area to the left of a z-score:



z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359
0.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5753
0.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141
0.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517
0.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879
0.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224
0.6	.7257	.7291	.7324	.7357	.7389	.7422	.7454	.7486	.7517	.7549
0.7	.7580	.7611	.7642	.7673	.7704	.7734	.7764	.7794	.7823	.7852
0.8	.7881	.7910	.7939	.7967	.7995	.8023	.8051	.8078	.8106	.8133
0.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8830
1.2	.8849	.8869	.8888	.8907	.8925	.8944	.8962	.8980	.8997	.9015
1.3	.9032	.9049	.9066	.9082	.9099	.9115	.9131	.9147	.9162	.9177
1.4	.9192	.9207	.9222	.9236	.9251	.9265	.9279	.9292	.9306	.9319
1.5	.9332	.9345	.9357	.9370	.9382	.9394	.9406	.9418	.9429	.9441
1.6	.9452	.9463	.9474	.9484	.9495	.9505	.9515	.9525	.9535	.9545
1.7	.9554	.9564	.9573	.9582	.9591	.9599	.9608	.9616	.9625	.9633
1.8	.9641	.9649	.9656	.9664	.9671	.9678	.9686	.9693	.9699	.9706
1.9	.9713	.9719	.9726	.9732	.9738	.9744	.9750	.9756	.9761	.9767
2.0	.9772	.9778	.9783	.9788	.9793	.9798	.9803	.9808	.9812	.9817
2.1	.9821	.9826	.9830	.9834	.9838	.9842	.9846	.9850	.9854	.9857
2.2	.9861	.9864	.9868	.9871	.9875	.9878	.9881	.9884	.9887	.9890
2.3	.9893	.9896	.9898	.9901	.9904	.9906	.9909	.9911	.9913	.9916
2.4	.9918	.9920	.9922	.9925	.9927	.9929	.9931	.9932	.9934	.9936
2.5	.9938	.9940	.9941	.9943	.9945	.9946	.9948	.9949	.9951	.9952
2.6	.9953	.9955	.9956	.9957	.9959	.9960	.9961	.9962	.9963	.9964
2.7	.9965	.9966	.9967	.9968	.9969	.9970	.9971	.9972	.9973	.9974
2.8	.9974	.9975	.9976	.9977	.9977	.9978	.9979	.9979	.9980	.9981
2.9	.9981	.9982	.9982	.9983	.9984	.9984	.9985	.9985	.9986	.9986
3.0	.9987	.9987	.9987	.9988	.9988	.9989	.9989	.9989	.9990	.9990
3.1	.9990	.9991	.9991	.9991	.9992	.9992	.9992	.9992	.9993	.9993
3.2	.9993	.9993	.9994	.9994	.9994	.9994	.9994	.9995	.9995	.9995
3.3	.9995	.9995	.9995	.9996	.9996	.9996	.9996	.9996	.9996	.9997
3.4	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9998

APPENDIX B

Table of Standard Reinforcing Steel Bars

On quantity tables, show the length to the nearest inch and the weight to the nearest pound.

Anchor: #i1012869Table 1-7: Standard Reinforcing Steel Specifications

English Designations	Nomal Bar Diameter (Inches)		Weight (Lbs per LF)	Area (Sq Inches)
#3	0.375	3/8	0.376	0.110
#4	0.500	1/2	0.668	0.196
#5	0.625	5/8	1.043	0.307
#6	0.750	3/4	1.502	0.442
#7	0.875	7/8	2.044	0.601
#8	1.000	1	2.670	0.785
#9	1.128	1 1/8	3.400	1.000
#10	1.270	1 1/4	4.303	1.266
#11	1.410	1 3/8	5.313	1.563
#14	1.693	1 3/4	7.650	2.250
#18	2.257	2 1/4	13.600	4.000
1 1/4" Diameter Smooth	1.250	1 1/4	4.172	1.227

VITA

Name: Zhuting Mao

Address: Construction Science Department, Texas A&M University
3137 TAMU, Langford Bldg,
College Station, TX, 77843

Email Address: zhutingmao@gmail.com

Education: B.S., Shanghai Normal University, Shanghai, China, 2010
M.S., Texas A&M University, College Station, TX, 2012