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# A Decision Making Approach for Selection of Sustainable Pavements in Texas by Integrating Life Cycle Cost Analysis (LCCA), Life Cycle Assessment (LCA) of Environmental and Social Impacts

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A DECISION MAKING APPROACH FOR SELECTION OF SUSTAINABLE PAVEMENTS IN TEXAS BY INTEGRATING LIFE CYCLE COST ANALYSIS (LCCA), LIFE CYCLE ASSESSMENT (LCA) OF ENVIRONMENTAL AND SOCIAL IMPACTS

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# Dedication

To my family

# A DECISION MAKING APPROACH FOR SELECTION OF SUSTAINABLE PAVEMENTS IN TEXAS BY INTEGRATING LIFE CYCLE COST ANALYSIS (LCCA), LIFE CYCLE ASSESSMENT (LCA) OF ENVIRONMENTAL AND SOCIAL IMPACTS

by

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DISSERTATION

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for the Degree of

DOCTOR OF PHILOSOPHY

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# Executive Summary

A sustainable pavement can be defined as the one that minimally impacts future economic opportunities, social conditions, human health, and the environment and still fulfills the engineering objectives. Although a pavement as outlined above is not yet entirely feasible, continual effort from every stakeholder with a vision of achieving sustainable development is essential for the future of society. In this study, one such effort was initiated by proposing a framework for selection of pavement design based on sustainable development.

The concept of sustainability is widely believed to be founded on three criteria: economic, environmental, and social standards. Since the purpose of pavements it to provide service for many decades, assessing each criterion throughout the life of pavements is required, that is, based on life cycle assessments. Based on the review of information, the most widely used economic evaluation tool for pavements is Life Cycle Cost Analysis (LCCA), which has been proposed by the Federal Highway Administration (FHWA). Practitioners have started using Life Cycle Assessment (LCA) recommended by the International Organization for Standardization (ISO), which has been recently adopted by the FHWA to estimate environmental impacts. Although various tools are available, like social LCA (SLCA), for evaluating the social impact of products, there is no tool available for assessing the social impact of pavements. A detailed review of published literature revealed that LCCA, LCA, and SLCA are different from each other regarding computational effort, input requirements, outputs generated, and employed assessment methodology. Most of the research has focused on one particular approach rather than an integrated approach. Additionally, each tool is at a different level of advancement, which means the required data and analytical methods may still be in the developmental stage.

LCA provides the necessary information for decision-makers in selecting pavement designs, which minimally impacts the environment. However, it is observed that it has never been fully utilized in selecting pavement design and construction. The reasons might be due to a lack of standardized and validated databases for assessments, unavailability of well-defined

methodologies to assess impacts during some phases of pavement, and also transforming the environmental impacts into meaningful data understandable to civil engineers. Although researchers proposed performing social LCA, it was given low significance in sustainable assessments of pavements. The reasons for ignoring social impacts can be attributed to the unavailability of raw data (due to politics, geography, culture, etc.) or complexity of integrating (i.e., measuring, aggregating, and comparing) society-wide impacts, and lack of a standard methodology.

One more major area that is barely addressed in sustainable pavements is decision-making. The concept of sustainability is multi-criteria and multi-dimensional and requires the involvement of experts from various fields to be part of the decision-making process. Additionally, the sustainability tools provide a different output that makes decision-making process even more challenging. Since sustainability needs to be evaluated regarding economic, environmental, and social criteria, the group decision becomes a complex and often fuzzy problem. The review of information suggested that the integrated decision-making process for designing sustainable pavements has not been developed yet.

Based on the above discussion and literature review, it was concluded that the design and selection of sustainable pavements would require an integrated decision-making process. A tool for evaluating the social impact of pavements, filling in the LCA database gaps and evaluation approaches, and a systematic approach for comparing alternate pavement designs; thus, this dissertation is aimed to achieve the same.

A multi-criterion group decision model was proposed in this study by combining the Analytic Hierarchy Process (AHP), the Data Envelopment Analysis (DEA) based preference aggregation method, and the α- Particle Swarm Optimization (PSO) technique. The proposed decision model requires fewer inputs from decision-makers compared to conventional AHP. The advanced group decision model integrates the individual expert decisions into a group decision by maximizing the satisfaction of experts in the group and generates a clear solution.

This study also contributed towards filling some of the deficits in life cycle assessments. This study identified models and databases that are reliable and applicable to LCA of pavements and are accessible to practitioners. A procedure for estimating the environmental impacts, during scheduled maintenance operations, due to traffic delays was developed. Earlier researchers often overlooked this phase which can have a significant impact. In this study, more emphasis was given to Life Cycle Impact Assessment (LCIA) where the environmental emissions are converted into meaningful impacts. Guidance was provided for conducting LCIA, and a new method for normalization and weighting steps of LCIA was suggested. As this dissertation incorporated the three assessments, it opened an opportunity to understand the intertwined relations between each method, which helped to fill some research gaps.

The selection of pavement design based on social sustainability principles is also often ignored due to the complexity involved in the quantification of social issues (like violation of labor rights), throughout the life cycle of pavements. In this study, an approach for performing LCA-S (social LCA) was proposed by combining principles of LCA with stakeholder management. Also, this study also placed particular emphasis on identifying and quantifying possible social impact indicators to provide decision-makers an insight on differentiating various pavement designs at the designing and planning phases.

One such social indicator that can be reasonably quantified is traffic noise. There are multiple sources of traffic noise like the engine, exhausts, tire pavement interaction, etc. Out of these sources, traffic noise due to tire pavement interaction is predominant in highways, and each pavement surface generates a different level of traffic noise. The traffic noise levels can influence real estate values, reduce neighborhood social interaction, and can have adverse health effects which may lead to a relocation of residents. Hence, traffic noise can be a potential and significant differentiating factor for pavement design selection. Even though it is a fact that traffic noise can have severe adverse social impacts, there is no existing pathway to quantify the effects. Hence, this study suggested an indirect approach for estimating the impacts. Noise barrier walls are commonly constructed to reduce traffic noise levels to below the thresholds. Since various

pavements generate different levels of traffic noise, each pavement type needs an accurate height of barrier wall to keep the traffic noise at acceptable levels. The construction costs and emissions associated with building and maintenance of barrier walls can be used to make a decision. FHWA's Traffic Noise Model (TNM) Version 2.5 can be used to estimate the future traffic noise due to different pavement surfaces and also for estimating the noise wall barrier heights.

In the end, the proposed framework and developed methodologies were demonstrated through a fictional case study. Four pavement designs were developed to perform for 30 years. The design software and inputs required for various assessments were selected for the state of Texas. LCCA, LCA, LCA-S were performed for analyzing the impacts for 30 years. Within LCCA, agency costs for constructing and maintaining highways for 30 years was estimated. Also, expenses incurred to users during maintenance operations was estimated under user costs.

In LCA, ten air pollutants were assessed and then transformed into six impact categories. In LCA-S, traffic noise was calculated without barrier walls for 30 years and then barrier wall analysis was performed to keep the noise at acceptable levels. The height of wall required to maintain noise levels below threshold levels at 100 feet from the edge of the pavement was analyzed. The life cycle costs (construction and maintenance) of barrier walls was estimated and categorized as social costs. Similarly, the LCA was performed for barrier walls and six impact categories were classified as social emissions.

A decision-making template using traditional AHP was developed and eight experts from various fields like construction management, execution, environment, policy-making, etc., were asked to provide their judgments. Six experts chose Design 4 as the preferred and two experts chose Design 1. The group decision was generated based on the expert's individual inputs, and the group decision was in favor of Design 4.

Even though this dissertation delivered an integrated framework for selecting sustainable designs, it needs to be further enhanced by including the overlooked parameters. The framework needs to be validated by applying it to a real highway project.

# Table of Contents

# List of Tables

# List of Figures

# Chapter 1. Introduction

## 1.1. Inspiration for the Study

In 2006, a group of civil engineering leaders gathered to formulate a global vision for the civil engineering profession. They envisioned a very different world for civil engineers by 2025. The vision developed in this summit was "In 2025, civil engineers will serve as master builders, environmental stewards, innovators and integrators, managers of risk and uncertainty, and leaders in shaping public policy"(ASCE Steering Committee 2007).

It is apparent from the vision statement that civil engineers need to be more versatile in addressing global challenges. Currently, one global challenge society facing is the migration of people from rural to urban areas, which is progressively straining the already overburdened infrastructure. With increasing urban population, shrinking natural resources, lack of funding and climate change has necessitated the development of sustainable infrastructure as the principal requirement. Besides, communities currently are more aware of the relation between quality of life and infrastructure. Thus demands for sustainable energy, fresh water, clean air, and safe waste disposal is also growing  (ASCE Steering Committee 2007).

The driving force for this dissertation is to contribute towards developing sustainable pavements, which is a key infrastructure component and is an integral part of people's everyday life.

## 1.2. What is Sustainability and Why it is Important?

Currently, there is an increased impetus towards sustainable construction or development, but "sustainability" is still far from being well defined. This might be reason that most of the published literature often starts with a definition of sustainability or sustainable development. Additionally defining sustainability is more important as it describes the context in which sustainability is being applied  (McKenzie 2004). Table 1.1 shows some of the definitions that are widely used in the construction sector.

### Table 1.1 Sustainability and Sustainability Development Definitions

| S. N. | Definition | Reference |
|---|---|---|
| 1 | Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. | Brundtland et al. (1987) |
| 2 | Sustainability is not about threat analysis, sustainability is about systems. Specifically, it is about how environmental, economic, and social systems interact to their mutual advantage or disadvantages at various space based scales of operation. | National Research Council (US). Transportation Research Board. Committee for a Study of Transportation and Sustainable Environment (1997) |
| 3 | Sustainability is not an ‘add-on’ as often assumed by some; rather, it should be viewed as an ‘umbrella’ tool which helps business to identify and manage economic, environmental and social risks in an integrated way. | Azapagic (2003) |
| 4 | Design and operation of human and industrial systems to ensure that humankinds use of natural resources and cycles do not lead to diminished quality of life due to either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment. | Mihelcic et al. (2003) |
| 5 | Sustainable reflects the fundamental human desire to create a better future world and leave a positive and durable legacy. Sustainability emphasizes the integrated nature of human activities and therefore the need to coordinate decisions among different sectors, groups and jurisdictions. | Litman (2007) |
| 6 | Sustainability is broadly defined to mean systems that are able to meet the needs of current and future generations by being physically resilient, cost effective, environmentally viable, and social equitable. | Sustainable Critical Infrastructure Systems: A Framework for Meeting 21st Century Imperatives (2009) |
| 7 | Sustainable highway should satisfy lifecycle functional requirements of societal development and economic growth while striving to enhance the natural environment and reduce consumption of natural resources. | “FHWA\| Sustainable Highways Initiative \| Overview” (2015) |
| 8 | Contributes to favorable economic development and to the fulfillment of society’s transportation needs in a manner consistent with natural laws and human values. | Bueno, Vassallo, and Cheung (2015) |
| 9 | Creating and maintaining the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations. | US EPA (2016) |
| 10 | A set of economic, environmental and social conditions in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely, without degrading the quantity, quality or the availability of natural economic and social resources. Sustainable development is the application of these resources to enhance the safety, welfare, and quality of life for all of society. | “ASCE” (2016) |

It is evident from the definitions that researchers are in agreement that sustainable development needs to respect the human wellbeing and protect the environment while maintaining economic profitability. Most researchers call for "balance" between social, environment, and economy dimensions, however, a precise definition of "balance" has not been proposed (Veeravigrom et al. 2015). Bueno et al. (2015) said that the sustainable development is quite complex and challenging to define succinctly for practical applications.

Sustainability is a complex concept which has much ambiguity in its definition itself, but why is it still considered necessary for infrastructure development? Irrespective of not holding a standard definition, sustainability breaks the traditional ways of thinking and demands to push the boundaries of current practices. Thinking about developing sustainable infrastructure shifts from being reactive to being more proactive (Bal et al. 2013). Infrastructure industry has significant potential to reduce the impacts on the people and Mother Nature. Thinking in terms of sustainability can minimize the consequences of infrastructure development by including future risk in assessment and performing assessment comprehensively.

### 1.3. How Highways Impact Different Components (Economy, Environment, and Social) of Sustainability?

Rephann and Isserman (1994) examined the effectiveness of highway investment as an economic development tool. They concluded that the counties nearby of the major cities were the beneficiaries of economic growth as highways have positive impacts on household income of manufacturing and retail sectors (Kim and Han 2016).

Even though highways boosts economy, construction, and maintenance of highways requires significant monetary and environmental investment. On an annual basis, FHWA estimates that around $ 170 billion is needed for constructing and maintaining highways in US. However, federal, state, and local government are annually spending $91 billion or less. This lack of funding is further leading to deterioration of highways and impacting society ("ASCE | 2013 Report Card for America's Infrastructure | Roads: Overview" 2016).

The economic impact of current investment trends in surface transportation infrastructure was examined by Economic Development Research Group (2011). They estimated that on an average 31% of the US vehicle miles of travel (VMT) use deficient pavement which leads to higher operating costs, delays, accidents, etc. The economic and social consequences of further deterioration of the US national surface transportation systems are:

1) It will cost US $3 trillion by 2040, $1.1 trillion in added business expenses and nearly $1.9 trillion from household budgets.
2) It will reduce the productivity and competitiveness of US firms about global competitors.
3) It will impact the social life of families by forcing them to sacrifice vacations, cultural events, educational opportunities, reduction in health-related purchases, etc.
4) The US projected infrastructure deficiencies in the present extended scenario could cost the national economy more than 400,000 jobs by 2040.

Environmental impact assessment due to pavements has been less highlighted in comparison to monetary evaluation (Tatari and Kucukvar 2012). Kucukvar and Tatari (2013) mentioned that construction sector is major of natural resource depletion and a significant source of environmental pollutions, such as air, water, and soil, solid waste generation, land use, toxic wastes, health hazards, and global climate change. Buildings and infrastructure by themselves use around 30% of the raw materials and 25 % of the water annually in the US. Additionally, construction projects annually generate 164,000 million tons of waste and demolition debris, which accounts for about 30% of the content in landfills (Sustainable Critical Infrastructure Systems: A Framework for Meeting 21st Century Imperatives 2009).

It is evident that highways boost the economy and increases the quality of current life but on the other hand, highways significantly degrade environment for future generations and health of society. Also, inability to maintain all highways in good condition impairs the projected economic growth and wellbeing of the society.

### 1.4. What are the Challenges Moving towards Sustainable Highway Design and Construction?

The real challenge for moving towards sustainable design and construction is how to operationalize sustainability into practice. Gilmour et al. (2011), Ramani et al. (2011) and Zietsman et al. (2011) stated that there is a full acceptance of the concept that sustainable development is important, but the problem lies in how to integrate sustainable activities in the planning and the design phases by organizations. Adoption of sustainability principles in highway design and construction is weaker compared with other industries. The reasons for highway infrastructure lagging behind in adoption of sustainability are the failure to include sustainable principles into everyday activity of the project life cycle and lack of involvement of every stakeholder towards sustainable design and construction which is a paramount requisite (Rafindadi et al. 2014). For inclusion of sustainability principles, every stakeholder in highway design and construction should have fundamental knowledge about sustainability, awareness of each stakeholder actions, and their consequences.

The other practical problems hindering sustainable construction practices are:

1) The concept of sustainability is multi-dimensional, and the scope of sustainability is vast (AlWaer and Kirk 2012).
2) Each stakeholder (designers, users, owners, assessors, etc.) has different sustainable themes (AlWaer and Kirk 2012).
3) There are no standardized indicator sets for comprehensive and sustainable transport planning.
4) Conflict exists between convenience and comprehensiveness when assessing sustainability. Due to an emphasis on easy to measure goals and often ignoring goals that are complex, which may mislead the planning decisions (Litman 2007).
5) The sustainability assessments are either biased towards an environmental or an economic evaluation and fail to address overall sustainability by focusing

only on certain stages in the project's lifecycle (Bueno, Vassallo, and Cheung 2015).

6) A strong belief that sustainable construction will increase the construction costs. Thus financially constrained agencies often ignore during planning and design phase. The possible reasons for economic impacts are additional costs associated with adapting a new technology or new materials and delay in construction due to new adaptions (Saleh 2015).

### 1.5. What are the Present Sustainable trends in Highway Construction? A Review of Existing Tools, Methods and Drawbacks.

After reviewing substantial published literature on the sustainable construction of highways, it was observed that increasing efforts had been placed to include sustainability principles in highways through different paths in the last decade. Some researchers have focused on developing new materials, technologies that will reduce the impacts on the environment, and others focused on measuring sustainability. For instance, some research related to new materials are : Velasco et al. (2014) reviewed reuse of waste in bricks production, Kariyawasam and Jayasinghe (2016) developed cement stabilized rammed earth, Abousnina et al. (2015) proposed to use oil contaminated sand into construction, Behera et al. (2014) reviewed use of recycled aggregate from construction and demolition waste use in concrete, etc. Similarly, Dinis-Almeida and Afonso (2015) stated that warm mix recycled asphalt can be a sustainable solution. Jamshidi et al. (2016) evaluated various sustainable technologies that upgrade the binder performance grade in asphalt pavement construction.

These studies contributed significantly towards reducing the impact on the environment and enhanced knowledge in the area of sustainability. However, sustainability is not just about using recycled or new construction materials, or implementing a new technology. Undoubtedly, these changes contribute to increasing the sustainability, but often implementing these changes may not make a whole project as sustainable (Anderson and Muench 2013). Sustainability assessment methods are required to evaluate the overall sustainability of a project. Highway

sustainability assessment methods are one of the emerging areas of sustainability. Bueno et al. (2015) categorized the present sustainable evaluation approaches and procedures into three classes:

1) Traditional decision-making techniques like cost-benefit analysis (CBA), multi- criteria decision analysis (MCDA), life cycle assessment (LCA), and social life cycle assessment (SLCA).
2) Rating systems that evaluate and rate infrastructure projects depending on its sustainability performance.
3) Frameworks, guidelines and models employed for sustainability measurement.

Traditional decision-making techniques analyze sustainability assessment in detail; however, each decision-making method is focused only on examining one particular criterion of sustainability (economic, environmental, or social.). Earlier researchers performed life cycle assessments measuring environmental impacts of alternative pavement designs. However, social life cycle assessment of highways is still at a nascent stage and needs to be investigated further.

Among sustainability tools, rating systems gained more popularity among infrastructure projects, especially highways. The sustainable rating system is a list of best sustainable practices with a score associated with each practice. Projects are certified as bronze: silver, gold, platinum rated sustainable project based on the number of best practices implemented in the project (Veeravigrom et al. 2015).

### 1.5.1. Advantages of Sustainable Rating Systems

Rating systems are easy to understand, and projects are ranked and scored against sustainability performance (economic, environment, and social phases collectively). They are highly flexible, practical, and adaptable. The rating systems employ a holistic approach, and their assessments are based on a real understanding of sustainability concept (Bueno et al. 2015). They provide a reasonable context within which designers, contractors, and material suppliers can be innovative in their solutions (Veeravigrom et al. 2015).

### 1.5.2. Disadvantages of Sustainable Rating Systems

The primary focus of rating systems is on environmental aspects and the construction stage of the project. The rating system is not designed to assist planners in decision-making processes while selecting the most suitable design regarding sustainability (Bueno et al. 2015). Most of the rating systems ignore details due to pushing towards simplicity. It is hard to generate consensus on the items to be included/excluded. The desire to pursue more points in a rating system could undermine a good design and/or construction (Muench et al. 2012).

Sometimes rating systems assign more weight on certain activities. For instance, in all rating systems "new technologies" receive a positive score towards sustainability, however in all cases, new technologies will not be sustainable. For example, Tatari et al. (2012) found that WMA (warm mix asphalt) a relatively new technology (most considered sustainable) in highways was deemed to be less sustainable concerning total energy, Industrial Cumulative Exergy Consumption (ICEC), and Ecological Cumulative Exergy Consumption (ECEC). A WMA was found to consume more ecological resources and to have the highest proportion of consumption of renewable ecological resources. The results of this study showed that although the mixing phase is critical, it should not be the only phase to evaluate the amount of atmospheric emissions of pavements. The supply chain, which includes material production and transportation, is critical for a more comprehensive evaluation. Rating systems fail to capture such detailed analysis.

Similarly, "recycled materials" are considered more sustainable (in rating systems) than using virgin materials. It may not be true in all cases, for example, Huang et al. (2009) studied the impacts or benefits of using recycled materials like " waste glass", " incinerator bottom ash", "recycled asphalt pavements" instead of natural aggregates for asphalt pavement at London Heathrow airport. Glass replacement causes more energy use and emission, due to the high consumption rate of fuel in waste glass collection (442 MJ/t), compared to that of 42 MJ/t for aggregates quarrying. In this scenario even though "waste glass" is a recycled material, it environment more than virgin materials. Although waste glass requires more fuel consumption than aggregate quarrying, it should be kept in mind that the cost or process of naturally forming

aggregates is unquantifiable, and it may not be available in the future. Therefore, the concept of sustainability is project sensitive, and a comprehensive analysis is required for every project.

Veeravigrom et al. (2015) made an impressive and detailed review of 11 existing rating systems that apply to roadways and found out that despite "economy" being considered as one of the key dimensions of sustainability, economic dimension topics are included in less than four rating systems.

### 1.6. Need for the Study

Anderson and Muench (2013) performed a study on sustainability trends on highway projects in the US by evaluating 105 highway and bridge projects for sustainable design and construction practices at various life cycle stages. They evaluated projects based on Greenroads rating system. One of the major findings of the study is that an early emphasis on sustainability principles during project development phase may significantly contribute towards sustainability. Similar conclusions are made by Golubchikov and Badyina (2012) and Swarup et al. (2011) that if no attention towards sustainability is disbursed during the development process, there will be more chances of causing considerable environmental burden, with economic wastefulness and social deficiencies. Consideration of sustainable principles specifically into early planning and design have great potential for development sustainability (Spangenberg 2013 and James et al. 2016). Hence, designers and planners are considered as one of the key stakeholders who have a greater level of influence (Tsai and Chang 2012 and James et al. 2016).

It is utmost important for designers and planners to understand the long term influence of their designs/decisions on sustainability. To achieve this, they need systematic and comprehensive tools to assess their designs and decisions. Even though the rating systems are useful for ranking and comparing projects, they are not specifically designed to assist designers and planning engineers in selecting the most sustainable design (Bueno et al. 2015).

One more area of concern after assessments is decision-making. The concept of sustainability involves multiple dimensions (like economic, environmental, social) and may

include experts from various fields as part of the decision. Since group decisions are multi-factor and multi-actor, group decision-making becomes a fuzzy problem with high complexity, which is hard to process. Henceforth, there is a need for an efficient decision-making framework in selecting a superior pavement design based on the sustainability factors.

### 1.7. Motivation of the Study and Organization of Research

The design of pavement structure has significant potential to influence the overall sustainability of the project and currently there has no standard methodology to evaluate the various sustainability parameters, which solely relate to the pavement structure design. Hence, the primary focus of this study is to develop a framework for selecting the most preferred sustainable pavement structure design based on the economic, environmental, and social parameters.

The framework needs to be able to handle efficiently multiple criteria, experts from the different field of expertise, and it should aid decision makers in choosing a superior design. Hence, there is a need for the development of decision model that efficiently integrates multiple criteria and policy makers. This study proposes to use life cycle assessments to evaluate the sustainable parameters (economic, environmental, and social).Since life cycle assessments evaluate the impacts in detail throughout the life cycle of pavement, it provides a holistic picture to the decision makers.

To evaluate the economic parameter for designs the life cycle cost analysis (LCCA) tool is being implemented by highway agencies. LCCA is an analysis technique that builds on the true principles of economic analysis to evaluate over-all-long-term economic efficiency between competing for alternative investment options (Life Cycle Cost Analysis of pavement , 1998).

Quantifying the environmental impact of pavements is best accomplished using the life cycle assessment (LCA) approach. Pavements have been evaluated using the LCA methodology for over a decade, but it was mainly confined to research rather than actual practice. Even in published research, more emphasis was given to pavement materials, construction practices and often ignored critical impact phases like traffic delay effect during maintenance and construction.

Lack of reliable databases and methodologies, to evaluate impacts at all phases of pavements service life are the main reasons that are hindering the implementation of LCA into practice. One more area that is often missing in LCA of pavements is impact assessment, which focuses on transforming the environmental impacts (emissions) into meaningful data for decision-makers.

Social life cycle assessment (SLCA) is the tool that can evaluate the social impacts due to pavement design. SLCA is still maturing; its usage is more in the manufacturing sector than in highway construction. Lack of a standard methodology, massive scope, ambiguity over the selection of social parameters to be evaluated, lack of social impact database, etc., are the major drawbacks associated with SLCA. Also, there is no approved methodology of SLCA in construction.

Till now more efforts have been placed on evaluating only one parameter (either economy or, environment) through life cycle assessments for assessing various pavement designs. Performing only a single assessment misses the opportunity to see the intertwined relationships among evaluation methods and how methods complements each other.

The focus of the dissertation is on integrating various assessments such as LCCA, LCA, and SLCA, which are different to each other in terms of process and each method is at different level of advancement. This study addressed each assessment method individually with a motive of integrating them into decision-making.

### 1.8. Objectives

The following are the objectives formulated in developing a framework for the selection of the most preferred sustainable pavement design:

1) To propose a group decision multi-criteria model that integrates social, economic and environment dimensions of pavements.
2) Identify the intertwined relationships between economic and environmental life cycle assessments.

3) To thoroughly evaluate the current practices of pavements life cycle assessments and to identify reliable data sources for practitioners. To develop a methodology for including traffic delay emissions during maintenance into LCA. To develop impact assessment methods to transform environmental impacts into meaningful data.
4) To propose a method for performing social life cycle assessment of pavements by identifying the indicators for assessing the social impacts that are relevant to the pavement construction.
5) To demonstrate the process of group decision-making through a case study.

# Chapter 2. Framework for Selection of Pavement Design based on Sustainability Principles

## 2.1. Development of Framework

The main idea for developing a framework is to help designers, project managers, and highway agencies in achieving the goal of sustainable development. Thus, the purpose of this study is to develop a framework which is comprehensive, practical, useful, and adaptable for various applications. In developing the framework, this study followed approaches proposed by:

1) "Bellagio STAMP: Principles for sustainability assessment and measurement." (Pintér et al. 2012).
2) "Sustainability assessment of transport infrastructure projects: a review of existing tools and methods." (Bueno et al. 2015).

Both these studies explicitly specified the requirements of a good sustainable assessment framework. The study by Pintér et al. (2012) was not specifically related to pavements, but recommendations by Bueno et al. (2015) were especially for pavements. The principles proposed by both studies are included in Table 2.1.

**Table 2.1 Requirements of Sustainability Assessment**

| S.no | Pintér et al. (2012) | Bueno et al. (2015) |
|---|---|---|
| 1 | ***Scope:*** An appropriate time horizon to capture both short and long terms effects. | ***Full approach:*** Analyze widest range of impacts that addresses three pillars of sustainability. |
| 2 | ***A proven conceptual framework:*** Appropriate cause and effect models | ***Life Cycle approach:*** Assess whole life cycle of the project. |
| 3 | ***Reliable Indicators:*** The use of standardized measurement methods, indicators with values and benchmarks. | ***Rigorous tradeoffs:*** Use analytical and rigorous mechanisms to compare all tradeoffs among economic, environmental and social aspects. |
| 4 | ***Transparency:*** Choices, assumptions, and uncertainties must be explained. | ***Transparent approach:*** Assessments should be transparent, rational and formal to minimize ambiguity. |
| 5 | ***Effective Communication:*** Assessments must be presented in a fair and objective way. | ***Adaptability to the context:*** Ability to address the context sensitive nature of sustainability. |
| 6 | ***Informative and hassle free:*** Communication and easy to use by wide range of people. | |
| 7 | ***Capable of continuous enhancement:*** Assessment practice must be responsive and the capacity to learn and adapt. | |

It is evident from Table 2.1 that sustainable assessment requires a robust and systematic approach. The following characteristics were selected for developing the framework for selecting the most sustainable pavement design.

### 2.1.1. Scope, Approach, Reliable Indicators, and Feasible Indicators

Employ a comprehensive approach to evaluating the environmental, social, and economic impacts of a pavement during its service life. Implement the life cycle assessment approaches for estimating the impacts. Indicators describe the state or level of an impact, and they assist in assessing and comparing impacts among various designs. The objective of this study is to choose indicators that are realistic and reliable.

### 2.1.2. Rigorous Tradeoffs and Adaptability to the Context

Life cycle approach (whether environmental, economic, or social) is complex and requires assumptions for simplification. The assumptions made in one assessment method should be in harmony with other assessment approaches. Also, identify the intertwined relationships of the economy, the environment and social life cycle assessments, which will help in closing some of the gaps in each method.

The framework should be flexible to address context sensitivity nature of sustainability and be adaptable to the framework of the study.

### 2.1.3. Effective Communication and Transparent Approach

Decision makers are to inform adequately about the assumptions in the assessment and the risk associated with them. The employed risk assessment and sensitivity approaches mesuring the risks associated with assumptions and choices needs to be communicated as well. The assessments should be transparent and clear to all decision-makers and stakeholders.

### 2.2. Decision-Making and Research Approach

Decision model should be capable of integrating various methodologies and facilitate the involvement of a group of diverse decision-makers. The objective to develop a framework was addressed by researching on four principal components namely:

1) Life Cycle Cost Analysis (LCCA),
2) Life Cycle Assessment of Environment impacts (LCA-E),
3) Life Cycle Assessment of Social impacts, and
4) Sustainable decision-making models,

This study proposes to use three life cycle assessment approaches (economic, environmental, and social) to evaluate various pavement designs. **Error! Reference source not found.** shows the typical life cycle of pavement and the assessment methods to evaluate sustainability. Each assessment will yield different outputs which are distinct from one another. Hence, a systematic approach is required for decision making.

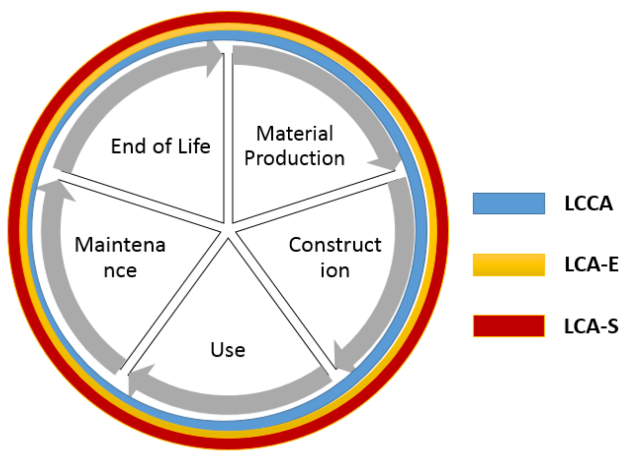



**Figure 2.1 Pavement Life Cycle and Assessments**

### 2.3. Life Cycle Cost Analysis

In LCCA, various costs such as construction, maintenance, user costs, etc., are calculated, and the initial construction and future costs are then converted to present costs or average annual costs. The calculated present or average annual costs of all possible designs can then be compared

while selecting the most suitable design. FHWA has developed a LCCA software product named RealCost2.5 to perform the numerical calculations. Many highway agencies in the US have adopted LCCA to analyze alternative designs by using RealCost2.5 (Rangaraju et al. 2008). However, LCCA is being implemented as a deterministic analysis which means all the future costs and other factors are considered as a unique, determined values. In reality, there will be uncertainties involved and risk assessment method is required to handle these risks. This study proposes to use a combination of deterministic and risk assessment approaches.

### 2.4. Life Cycle Assessments of Environment Impacts

In recent years' environment impacts due to pavements are being evaluated by Life Cycle Assessment (LCA). LCA comprehensively quantifies the emissions and energy flows of a pavement in its life cycle. International organization of standardization (ISO) released two standards ISO 14040 2006 and ISO 14044 2006 to standardize the LCA methodology and to ensure consistency in performing LCA. Detailed procedure for conducting LCA, is available in an EPA document (SAIC 2006) similar to ISO standards. However, they are not specific for LCA of pavements. At present, there is no government issued guidelines in North America regarding LCA-E for pavement (USDOT, FHWA 2014).

Ironically, Anderson and Muench (2013) observed that LCA has never been achieved in highway design and construction. The reasons might be the existing limitations of LCA, like lack of standardized and government approved databases for assessments and also more effort required to perform the assessment.

However, LCA studies on pavement designs have been performed by various researchers like Weiland and Muench (2010), Nisbet et al. (2000),Vidal et al. (2013),Tatari et al. (2012), Mroueh (2000), Liu et al. (2014), Santero et al. (2011), Huang et al. (2009), Barandica et al. (2013), Anastasiou et al. (2015), Thiel and Len (2014) ). These researchers estimated the emissions with inspired efforts. However, most of the research ended at estimating the emissions only. Emissions need to be converted into meaningful impacts to aid the decision-making process. Another key

factor that was being ignored in LCA is environmental impacts due to traffic delays caused by scheduled maintenance and rehabilitation. Since the dissertation is proposing a new approach to performing social life cycle assessment which is based on LCA, the environmental LCA will be referred as LCA-E from now on while social life cycle assessment will be referred as LCA-S to minimize confusion.

This study aspires to contribute towards LCA-E of pavements in three ways:

1) Identify reliable databases and methods to perform LCA-E.
2) Develop method for normalization of emissions into meaningful impacts.
3) Develop a methodology for estimating environmental impacts due to traffic delays caused during scheduled maintenance and rehabilitation.

### 2.5. Social Life Cycle Assessment

Similar to economic and environmental impacts, social impacts need to be considered for design selection. Assessing social impacts throughout the life cycle of pavement is still at a nascent stage. There is no standard framework for conducting social life cycle assessment (LCA-S) in design and construction like environmental and economic assessments. Few researchers attempted social life cycle assessments of pavements (Thorpe 2013 and Stevenson 1995) and some appraised social impacts (especially workers safety) in other construction sectors like buildings (Gatti et al. (2012),Behm (2005), Gambatese et al. (2008), Toole and Carpenter (2011) ,Zhao et al. (2012), Gilchrist and Allouche (2005)).

The significant drawbacks with social assessments are the lack of standard methodology, lack of databases on social impacts, a need of multi-disciplinary expertise, selection of social impact indicators that are practical and comprehensive, etc.

This study aims to contribute towards LCA-S of pavements in three ways:

1) Propose a framework for performing LCA-S
2) Identify possible social impact indicators about pavement design selection.
3) Perform social impact assessment for various pavement types.

During the preliminary investigation, it was observed that the assessment systems LCCA, LCA-E, and LCA-S are different from each other regarding the process and are at a various level of advancement. The study also observed that there are intertwined relationships between economic, environmental, and social life cycle assessments, which has never been investigated before, even though this assessment approaches complement each other. For example, detailed cost estimates in LCCA for each activity (including machinery and manpower) helps in LCA-E and LCA-S.

### 2.6. Sustainable Decision-Making Models

It is apparent that sustainable decision-making is a multifaceted and involves multiple criteria. An efficient approach is required to select a preferable design. A detailed study on various multi-criteria decision models is needed. Since sustainability concept involves various concepts, to make sure experts from different fields are part of decision-making, a heterogeneous group is typically formed. It is very seldom that all decision makers in the group are in consensus with each other and just averaging all decisions may lead to the selection of an odd design. This study plans to develop a decision-making tool which can handle multiple criteria (both subjective and objective measures), maximizes the satisfaction of decision makers in the group, and uses straightforward analytical approaches. Figure 2.2 displays the proposed framework for this study. Figure 2.3, Figure 2.4, Figure 2.5, and Figure 2.6, respectively shows the details of proposed frameworks for performing LCCA, LCA-E, LCA-S, and decision-making process. A case study was conducted to demonstrate the proposed framework. The present study focused on selecting alternate designs, but the same methodology is useful for various other applications like the selection material, equipment, process, etc. Various publications support this framework and case study as listed in the next section.

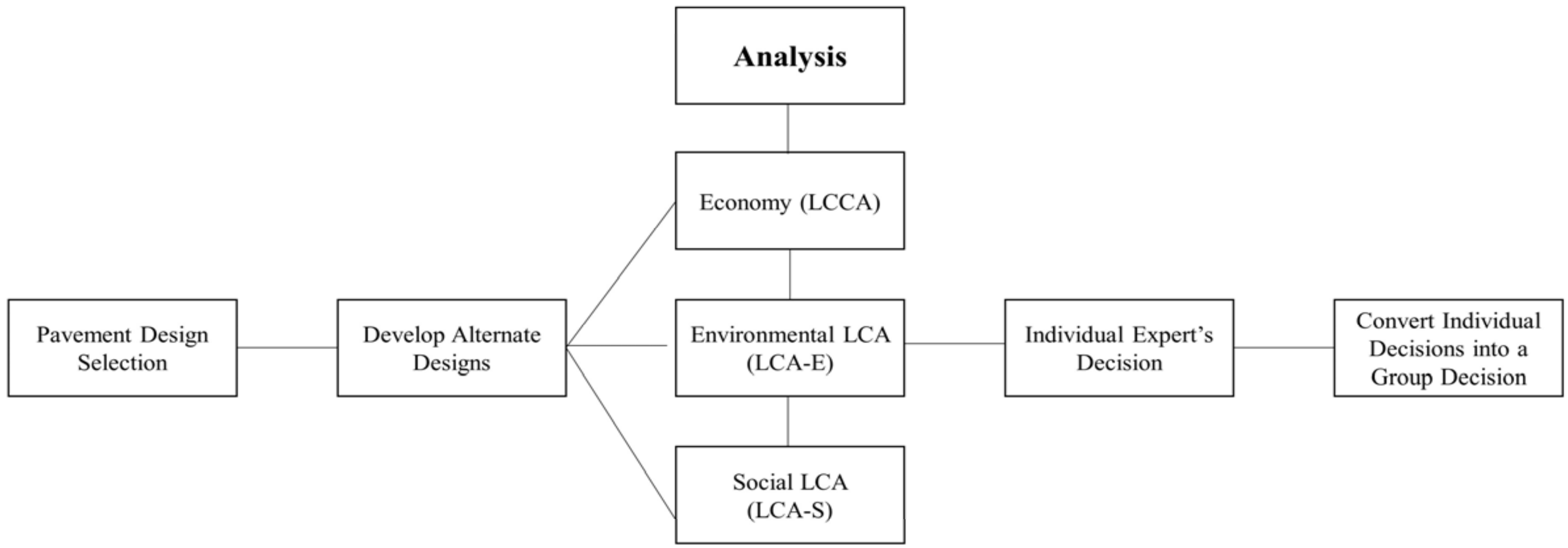



**Figure 2.2 Proposed Framework for Selection of Pavement Designs**

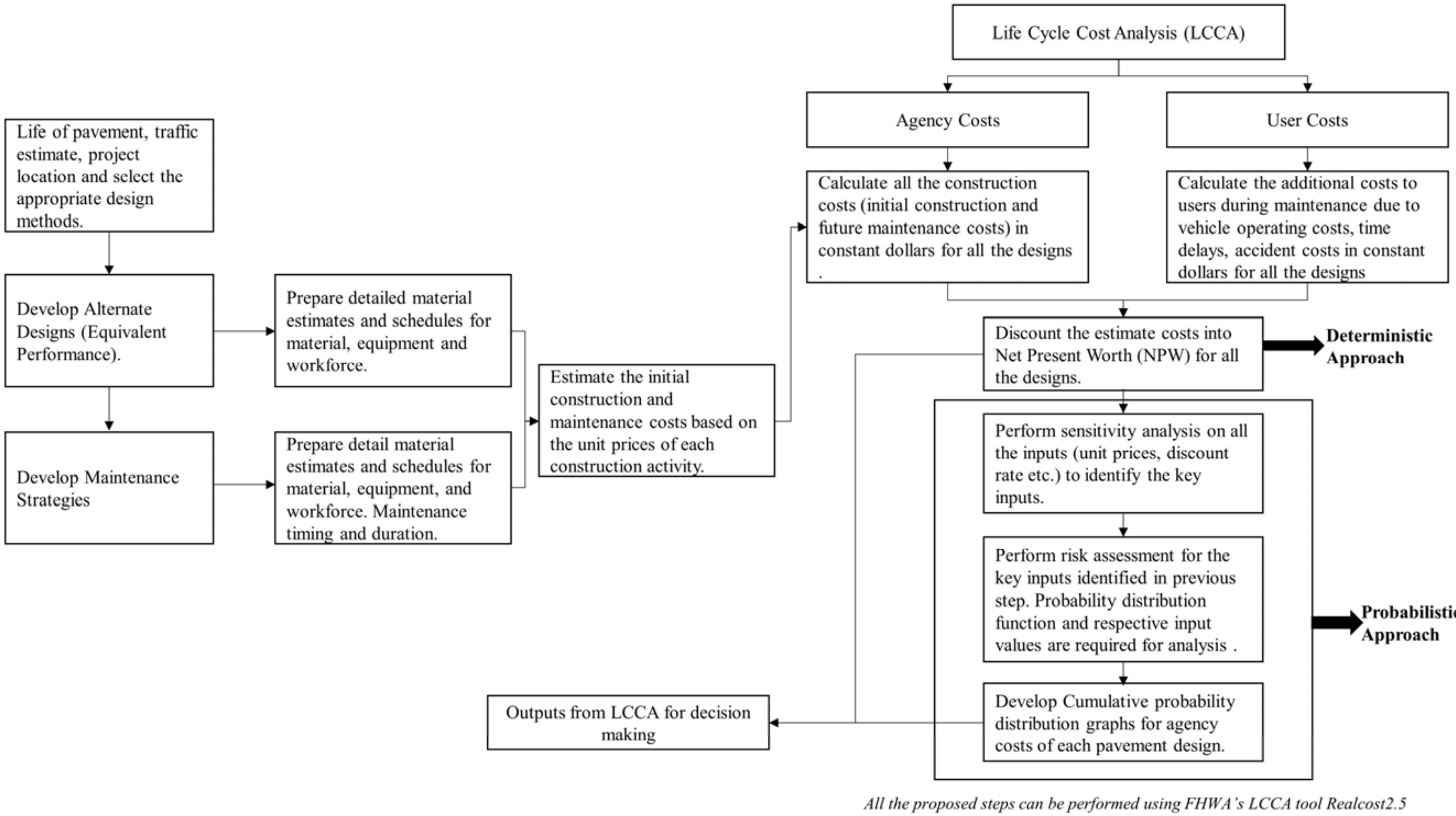



**Figure 2.3 Proposed Framework for Performing LCCA**

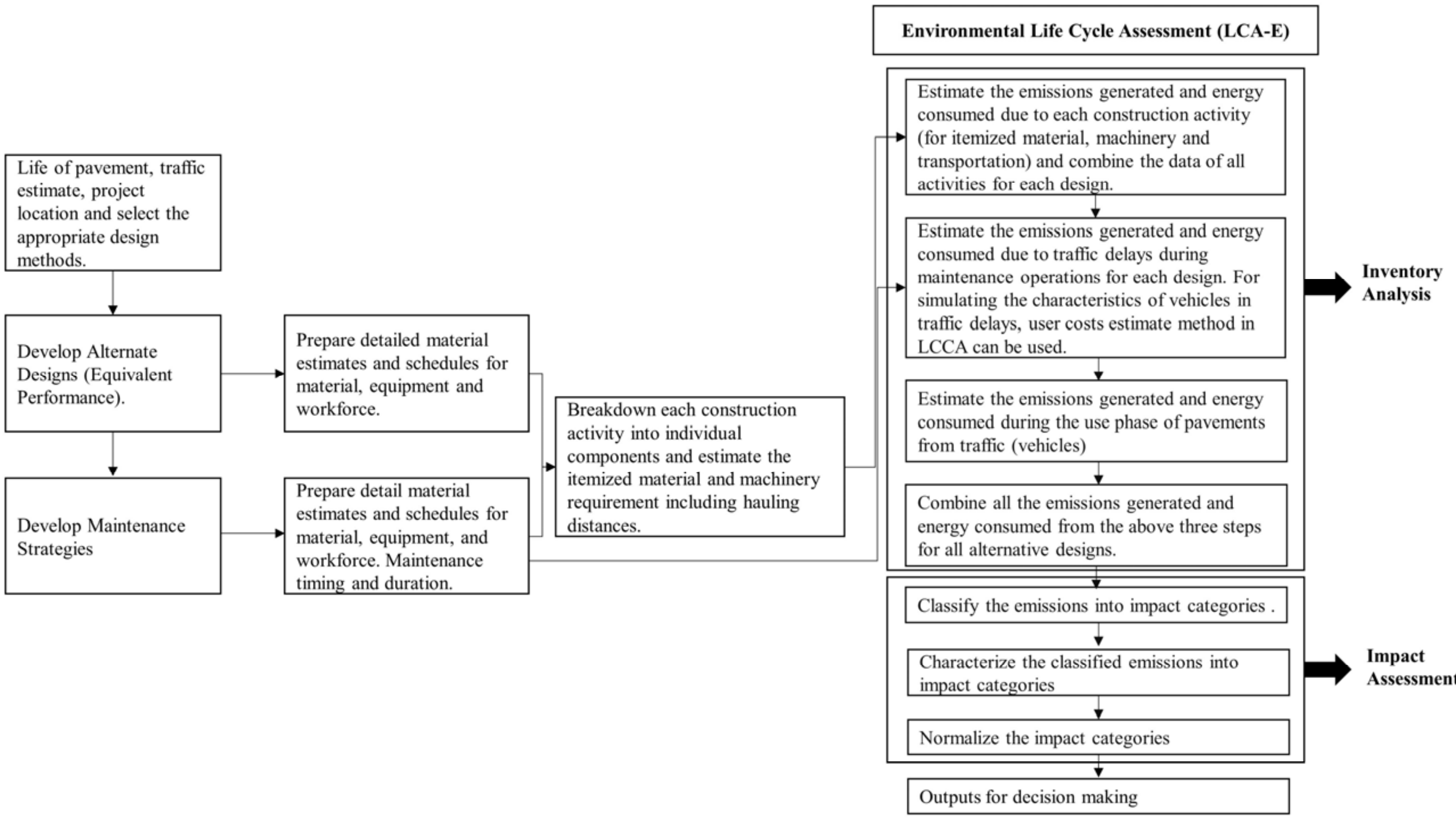



**Figure 2.4 Proposed Framework for Performing LCA-E**

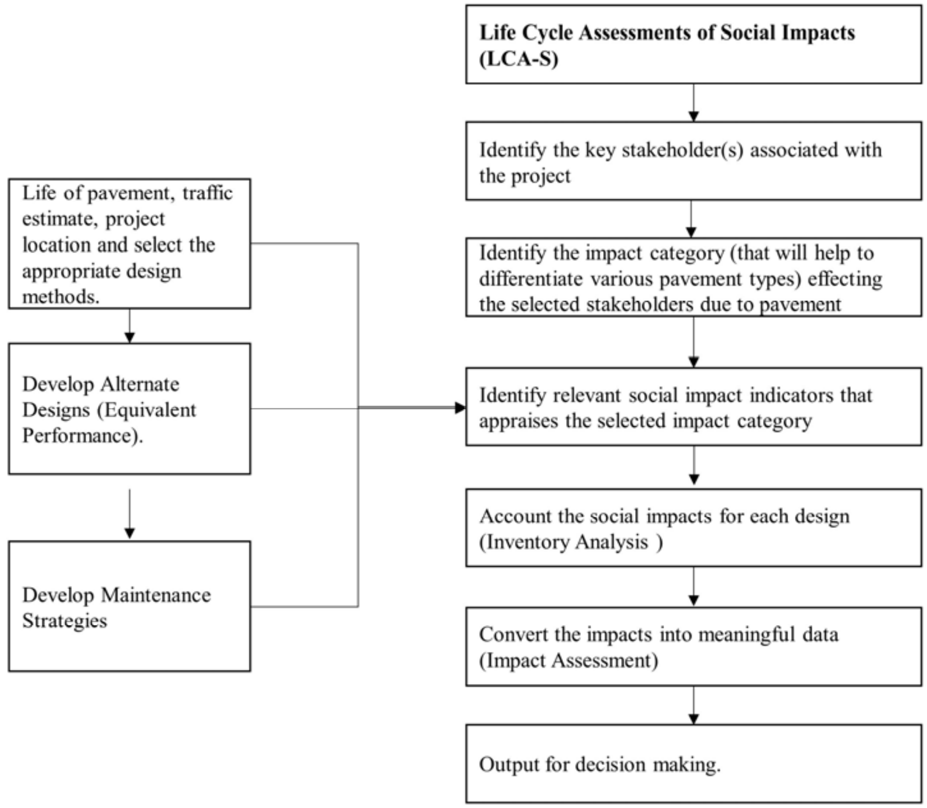



**Figure 2.5 Proposed Framework for Performing LCA-S**

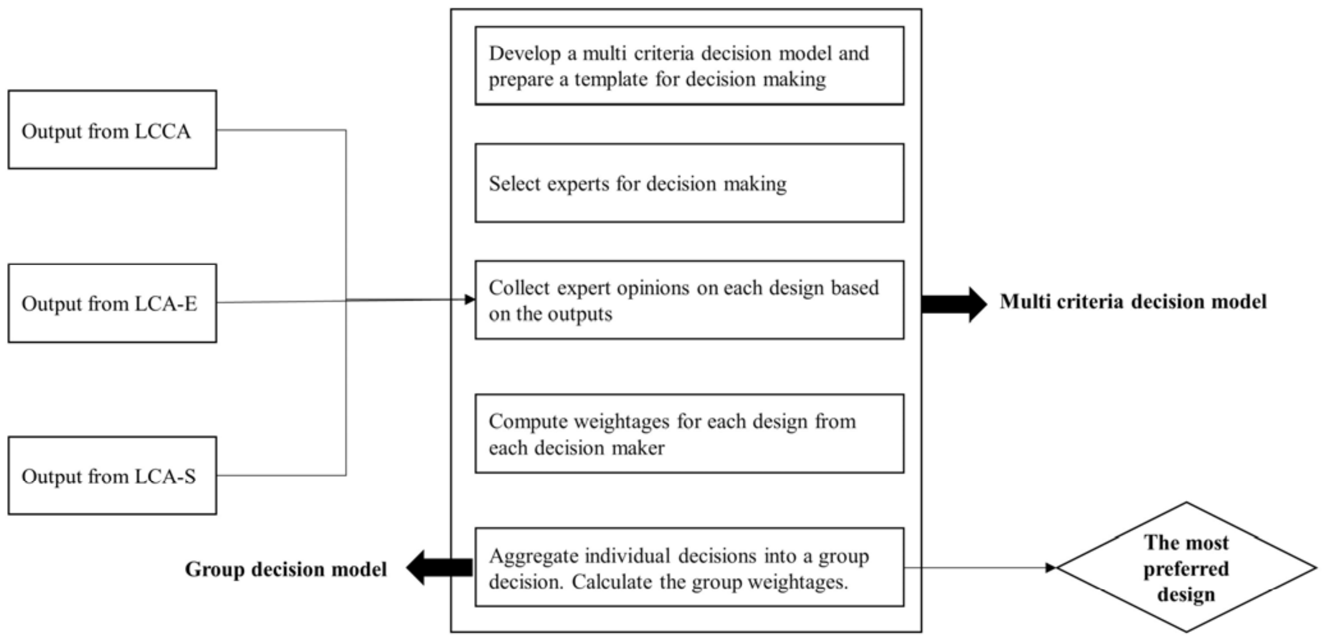



**Figure 2.6 Proposed Framework for Decision Making**

## 2.7. Publications

### 2.7.1. Life Cycle Assessments

1. Inti, S., Sharma, M., and Tandon, V. (2016). "*An Approach for Performing Life Cycle Impact Assessment of Pavements for Evaluating Alternative Pavement Designs."* Procedia Engineering, 145, 964-971.
2. Inti, S., Sharma, M., and Tandon V. (2016). "*Enhancing pavement design selection by incorporating normalization into life cycle impact assessments.*" International Conference on Transportation and Development. Vol. 2016. 2016.
3. Inti, S., Martin, S. A., and Tandon, V. (2016). "*Necessity of Including Maintenance Traffic Delay Emissions in Life Cycle Assessment of Pavements."* Procedia Engineering, 145, 972-979.

### 2.7.2. Social Life Cycle Assessments

1. Inti,S., Tandon,V.,(2015) "*Feasibility Evaluation of Social Life Cycle Assessment Inclusion in Pavements."* Presented at the Conference of Transportation Research Group of India (CTRG2015) held in Kolkata, December 17-20, 2015.
2. Inti, S., and Tandon.V. "*Noise as a Social Impact Indicator for Selection of Sustainable Pavements.*" Submitted for possible publication in Journal of Cleaner Production on 09/09/2015.

### 2.7.3. Decision Model

1. Inti, S., and Tandon, V., "*Application of Fuzzy Preference AHP Logic in Evaluating Sustainability of Transportation Infrastructure Requiring Multi Criteria Decision-making.*", Submitted for possible publication in Journal of Infrastructure Systems, ASCE on 03/16/2015.

2. Inti, S., and Tandon, V., "*Aggregation of Individual Decisions Using Data Envelopment Analysis (DEA) Based Preference Aggregation Method Combined With α-PSO (Particle Swarm Optimization).*" Accepted for publication in Journal of Computing in Civil Engineering ASCE, on 04/25/2016.

# Chapter 3. Selection of Sustainable Pavement Design

Even though the concept of sustainability and use of group decision-making in selecting among alternatives has been separately practiced for decades, the selection of sustainable alternatives using group decision-smaking has not been attempted and is the focus of this study. To better comprehend the process, alternative pavement designs were proposed and evaluated based on sustainability principles. In the end, a sustainable pavement design was selected by an expert panel using integrated group decision-making process. In this chapter, the sustainable pavement design selection process is presented.

## 3.1. Pavement Design Alternatives

To achieve objectives of this study, a case study for selecting the most preferred design from four equivalent pavement designs were proposed (Figure 3.1) which are expected to provide service for 30 years. Equivalent design implies that each design alternative is expected to perform equally during its design life (provides the same level of service, over the same performance period, and has similar life-cycle costs), based on the concept proposed by Stephanos (2008). Three similar designs were flexible pavement designs while the fourth pavement design was rigid pavement. The flexible pavement design was developed using FPS 21 (TxDOT design program) while the rigid pavement design was developed using the AASHTO Design Guide. The rigid pavement design consists of Continuously Reinforced Concrete Pavement (CRCP) surface layer. The design software was selected based on the recommendations of the Texas Department of Transportation pavement design guide (Russel Lenz.W 2011).

Each of the pavement design is expected to carry Annual Average Daily Traffic (AADT) of 61,236 on each side in 2014 on a six lane highway (three lanes on each side). The traffic consisted of 10.6% of trucks and 89.4% of passenger cars, and annual traffic growth is assumed to be 0.75% for next 30 years. Subgrade conditions were considered the same for all design alternatives. The three flexible pavement designs varied in their material composition and thickness of layers. On average, the flexible pavement design is expected to have two

rehabilitations during 30 years of service life. The fourth design is not expected to require any major rehabilitation for 30 years. Although major rehabilitation of rigid pavement is not supposed, a minor maintenance (repairing two patches 10’ by 20’ for every lane mile at 20 years) for rigid pavement is assumed in the study. Appendix A shows the performance details of each design.

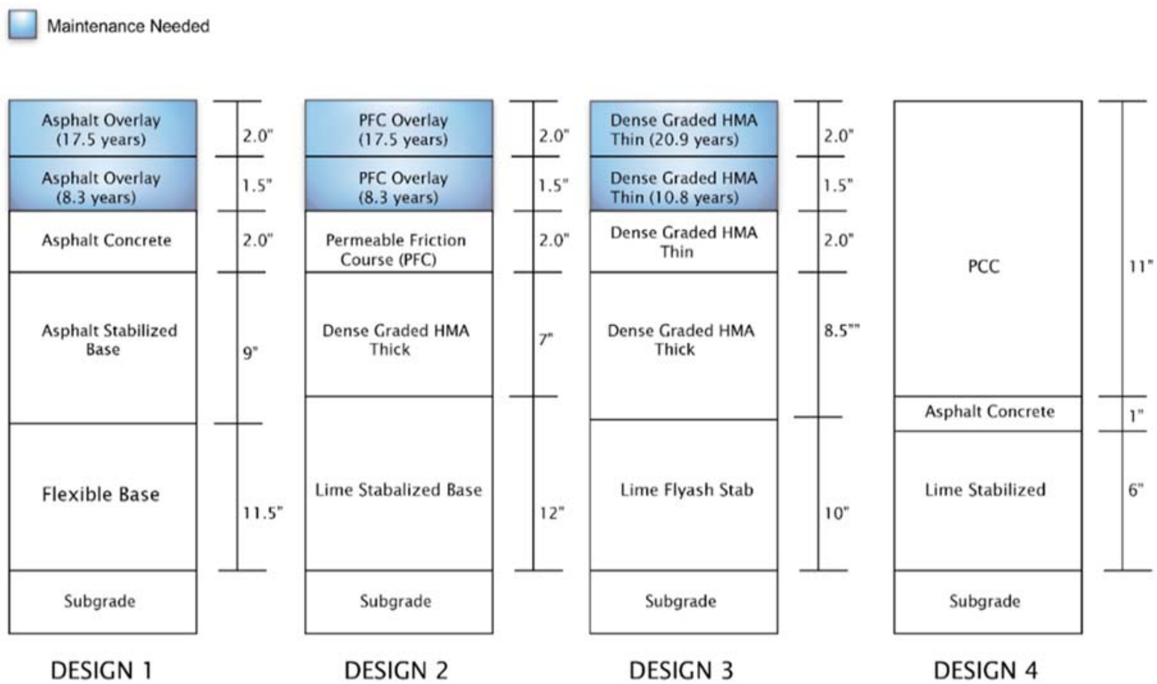



**Figure 3.1 Alternative Pavement Designs**

### 3.2. Life Cycle Cost Analysis (LCCA)

One of the sustainability pillars is economics and LCCA is the most commonly used tool for performing the economic impact. The LCCA includes all costs incurred, during its service life cycle rather than at the time of construction (AASHTO Pavement Design Guide). The main benefit of LCCA is that it provides information and understanding of expenses incurred during service life rather than initial costs. The initial and predicted schedule of activities and their associated agency and user costs from the projected life-cycle cost stream, for each design, is included in the analysis. Any future activity and related expenses during service life are estimated in constant dollar terms

by translating them to present worth using a real discount rate (commonly known as discounting). LCCA Primer FHWA (2002) advocates that if LCCA is being used to compare various designs, the discount rate and the analysis period should be same for all alternatives. The probabilistic approach is used to calculate variability and uncertainty in the LCCA and discussed in the following subsections.

In the deterministic approach, the LCCA applies procedures and techniques without considering the variability of the inputs. Data like construction costs, discount rates, etc. are the best-predicted values. However, the variability in data is not considered. In the risk analysis approach or probabilistic approach, the variability in the inputs is found. The Interim Technical Bulletin by Walls and Smith (1998) recommends this approach because it combines probability descriptions of analysis inputs with computer simulations to generate the entire range of outcomes as well as the likelihood of occurrence.

Rangaraju et al. (2008) conducted research to evaluate LCCA practices among state highway agencies (SHA's) for pavement selection and reported that 81 percent of SHA's (17 out of 21) are still using deterministic approach while only one SHA is using probabilistic approach (Rangaraju et al. (2008)). The remaining 14 percent (3 out of 21) SHA's are using a combination of deterministic and probabilistic approach. The probabilistic approach is not in practice due to input complexity. In this study, a combination of deterministic and risk analysis approach was used for conducting LCCA using RealCost 2.5 software developed by FHWA.

### 3.2.1. Deterministic Approach

RealCost2.5 is a Microsoft Excel-based software for numerical calculations and calculates LCCA using both agency and users costs incurred during pavement service life. Although required for the analysis, some of the costs are unavailable or may not impact analysis significantly; therefore, they were not considered in this study and will be discussed in appropriate sections.

#### *3.2.1.1. Agency Costs*

Agency costs are costs directly incurred by agencies (SHA's or Construction firms) in a pavement service life. In addition to construction and maintenance costs, costs associated with the demolition of pavement at the end of life are also agency costs. In this study, end of life cycle costs was not considered because pavements are not typically demolished and thrown away in the landfill. In such cases, pavement salvage value can be assigned to the pavement which will be a negative cost (savings) based on the remaining service life of pavement. In this study, the salvage value was not considered because information related to the salvage value of different pavement types is not currently available and all pavements were designed approximately for 30 years. For estimating agency costs during construction and maintenance operations, the costs were estimated for the 1-mile length of the pavement section for each pavement design of Figure 3.1.

The unit prices or costs for the various pavement layers were obtained from the average low bid prices of El Paso district published by Texas Department of Transportation, (TxDOT) ("Average Low Bid Unit Prices" 2014) and R.S. Means data 2012 (R.S. Means 2012).

Since R.S. Means cost data are typically based on national averages for materials and installation, adjustments need to be made using location factors. Additionally, 2014 costs need to be adjusted using historical cost indexes (the historical cost index for 2012 and 2014 were 194.6 and 202.7, respectively). Cost adjustments were done using the following equation:

$$\frac{Index\ for\ Year\ A}{Index\ for\ Year\ B} \times Cost\ in\ Year\ B = Cost\ in\ Year\ A \qquad \textbf{3.1}$$

The unit prices of various pavement items are summarized in Table 3.1. Although not included in Table 3.1, the detailed cost breakup for each item including material costs and quantities, machinery type, and hours (working and labor) were maintained separately along with the mix designs of various items (concrete, stabilized bases, asphalt mixes) for use in estimating emissions for LCA analysis.

All future costs and initial construction costs were calculated by multiplying the unit process with quantities required and constant dollars were used in estimating the future costs. Constant dollars indicates the unit prices of the future costs are same as the present costs. The future costs were converted to the present worth using a discount rate of 4%.

**Table 3.1 Input Costs of Various Items**

| Item Description | Unit | Price | Remarks |
|---|---|---|---|
| Asphalt Concrete (AC) Surface 2" thick | SY | $7.70 | Excludes Hauling |
| Asphalt stabilized base 9" thick | SY | $34.50 | Excludes Hauling |
| Flexible Base 11.5" thick | SY | $12.30 | Excludes Hauling |
| Subgrade Preparation | SY | $3.2 | No need of Hauling |
| Prime Coat (0.30 Gal per SY) | 1,000 SY | $1.6 | Excludes Hauling |
| Tack Coat (0.10 Gal per SY) | 1,000 SY | $0.6 | Excludes Hauling |
| Hauling costs | Ton | $7.7 | Costs estimated for truck 16.5 CY, 15 min wait/loading/un loading 35 MPH average Cycle 24Miles. |
| AC Overlay 1.5" Thick | SY | $5.30 | Excludes Hauling |
| AC Overlay 2.0" Thick | SY | $6.90 | Excludes Hauling |
| Milling | SY | $1.40 | Excludes Hauling |
| Permeable Friction Course 2" Thick | SY | $11.5 | Excludes Hauling |
| Permeable Friction Course 1.5" Thick | SY | $8.60 | Excludes Hauling |
| Dense Graded HMA 7.0" Thick | SY | $29.0 | Excludes Hauling |
| Lime Stabilized Base 11.5" Thick | SY | $15.0 | Excludes Hauling |
| Dense Graded HMA Thin 2.0" Thick | SY | $7.80 | Excludes Hauling |
| Dense Graded HMA Thick 8.5" | SY | $27.5 | Excludes Hauling |
| Lime Flyash Stabilized Base 10" Thick | SY | $15.0 | Assumed 6% Lime |
| Dense Graded HMA thin 1.5" Thick | SY | $6.70 | Excludes Hauling |
| Portland Cement Concrete 11" Thick | SY | $56.0 | Includes the reinforcement, excludes hauling |
| Lime Flyash Stabilized Base 6" Thick | SY | $12.0 | Excludes Hauling |

#### *3.2.1.2. User Costs*

In the simplest sense, user costs are costs incurred by the highway user over the life of the project. User costs are an aggregation of three separate cost components: vehicle operating costs (VOC), crash costs, and delay costs.

To estimate VOCs, accurate pavement performance models, and a systematic methodology to quantify the difference in VOC rates for slight differences in pavement performance is needed.

Although required and is important, VOCs were not considered in this study due to lack of data availability. Additionally, if the performance levels remain good, and the performance of all alternative designs is similar then the VOCs influence of each pavement type will be same. Thus the influence of VOC on the selection of sustainable design will be minimal. In this study, crash costs were not considered due to lack of statistical data for crashes based on the pavement type. Again, the influence of skid resistance, hydroplaning, etc. will significantly influence crash costs but were not considered due to data unavailability. Thus only user delay costs were considered in this study.

User delay costs are significant and need to be considered for evaluating sustainability. The user delay can happen at the time of initial construction, an accident on the road, traffic congestion on a daily basis during peak hours, detour traffic from other highways, climatic adversities, maintenance, etc. Although significant, some of the user delay costs will be similar for all pavement types. For instance, user delay during peak hours will be independent of pavement types. Similarly, TxDOT considers the number of construction days for both flexible and rigid pavement construction to be the same. Therefore, user delay costs will be similar for all pavement types. One user delay cost that can significantly influence is the delay during maintenance and rehabilitation operations which depends on the pavement type. Hence, user delay costs during maintenance operations were considered in this study.

RealCost2.5 can estimate the user delay costs during initial construction and maintenance of pavements. To eliminate initial construction user delays, Wimsatt et al. (2009) suggested entering zero in RealCost2.5. The delay costs will be different for vehicle types, and TxDOT provides user delay costs annually based on the annual consumer price index for the previous year and is included in Table 3.2 for the last four years. The user costs, summarized in Table 3.2, include additional vehicle operating costs (considered a typical value for all pavement types) incurred due to delays during construction and lost time to the users due to delays. In this study, the user delay costs of 2014 were used for sustainability evaluation.

In RealCost2.5, the user costs calculations are based on the traffic distribution during maintenance, queue dissipation capacity, work zone speed, work zone capacity, working hours during maintenance, weekdays or weekends, the number of lanes open to traffic, duration of maintenance, and a specified discount rate. The inputs required and values used in this study for estimating user delay costs are included in Table 3.3. These inputs are in addition to construction costs, maintenance costs, and timing of maintenance. The methodology used in estimating user delay costs can also be adapted in estimating emissions during maintenance operations in LCA (explained in LCA section). RealCost2.5 suggests to perform sensitivity analysis in case deterministic approach is used for LCCA analysis.

**Table 3.2 TxDOT User Costs for Last Four Years**

| Year | 2011 | 2012 | 2013 | 2014 |
|---|---|---|---|---|
| User Costs Car ($/Vehicle hour) | $20.35 | $20.99 | $21.42 | $21.73 |
| User Costs Truck ($/ Vehicle hour) | $29.71 | $30.65 | $31.28 | $31.71 |

**Table 3.3 Inputs Required by RealCost2.5 for Estimating User Costs due to Delays**

| Parameter | Value |
|---|---|
| Annual Average Daily Traffic (AADT) | 61,236 |
| Cars as Percentage of AADT (%) | 89.4 |
| Single Unit Trucks as Percentage of AADT (%) | 10.6 |
| Annual Traffic Growth | 0.75 |
| Speed Limit Under Normal Operating Conditions ,Miles per hour (mph) | 60 |
| Discount Rate (%) | 4 |
| No of Lanes in Each Direction During Normal Conditions | 3 |
| Free Flow Capacity ,Vehicles per hour per lane (vphpl) | 2,000 |
| Rural or Urban Hourly Traffic Distribution | Urban |
| Queue Dissipation Capacity (vphpl) | 1,818 |
| Maximum AADT (total for both directions) | 75,102 |
| Work Hours | 9AM-5PM |
| Work Zone Speed (miles per hour) MPH | 40 |
| Work Zone Length | 2 |
| No of lanes opened in Each Direction | 2 |
| Maximum Queue Length (Miles) | 5 |
| Work Zone Capacity (vphpl) | 1,415 |

### 3.2.2. Probabilistic Approach

In addition to the deterministic approach, the probabilistic analysis was conducted for economic analysis to account for variability and uncertainty. The complete probabilistic approach was not performed due to lack of guidance in assuming the probability distributions for all inputs. The parameters used in the probabilistic analysis are included in Table 3.4 while remaining inputs were similar to the ones used for deterministic analysis (Tables 3.1 through Table 3.3).

**Table 3.4 Inputs Considered for Probabilistic Approach**

| Parameters | Probability Distribution | Value | Source | Remarks |
|---|---|---|---|---|
| Discount Rate | Triangular | Minimum=3%, Most likely =4.0 , and Maximum=7% | Assumed | Distribution function assumed as per Greenroads Manual v1.5 |
| Queue Dissipation Capacity | Normal | Average=1,818 vphpl, Standard Deviation =144 vphpl | Greenroads Manual v1.5 | |
| Value of Time for Passenger Cars | Triangular | Minimum=$21.23, Most likely =$21.73 , and Maximum=$23.23 | Assumed | |
| Value of Time for Trucks | Triangular | Minimum =$30.21, Most likely =$31.71 , and Maximum =$33.21 | Assumed | Distribution function assumed as per Greenroads Manual v1.5 |
| Work Zone Capacity | Normal | Average=1,415 vplph, Standard Deviation =200 vplph | Assumed | |
| Agency Construction Cost | Normal | Average=best estimate Standard Deviation =10% of the average | Greenroads Manual v1.5 | |

### 3.2.3. LCCA Results

The results of deterministic and probabilistic approach are included in Table 3.5 Since the study focused on comparing alternative designs, the difference in costs among designs was also calculated in aiding decision-makers. Design 3 has the lowest agency costs and Design 2 has the

highest, whereas in the case of user costs Design 4 has the lowest user costs, and Design 2 has the highest costs. The user costs were significantly influenced by the timing of maintenance. The user costs in Table 3.5 were considered for the scenario where maintenance happens from 9 AM – 5 PM. Maintenance during the night from 8 PM up to 7 AM yielded no user costs due to less traffic for all designs. But for this study 9AM-5 PM is considered as the working time as it will result in producing different user costs and beneficial in comparing alternative pavement designs. One of the issue to be kept in mind is the fact that construction safety barriers may still be there in the night with reduced speed signs suggesting drivers to drive at reduced speed. The speed signs may lead to reduced speed and slightly higher users' costs and was not included in this study due to unavailability of data.

**Table 3.5 Summary of LCCA Results for the Alternative Designs**

| Approach | Costs | | Costs Per Mile | | | | Comments |
|---|---|---|---|---|---|---|---|
| | | | D 1 | D 2 | D 3 | D 4 | |
| Deterministic Approach | Agency | | $3,306,163 | $3,539,272 | $3,014,442 | $3,449,628 | Sensitivity analysis indicates discount rate, work zone capacity, work zone speed, work zone timings influences values but rankings remained same. |
| | User | | $961,021 | $968,780 | $797,151 | $133,207 | |
| Probabilistic Approach | Agency | Minimum | $2,200,663 | $2,470,388 | $2,154,793 | $2,185,333 | Sensitivity analysis on simulations indicate the construction costs drives the results. Timing of rehabilitations kept constant during simulations. |
| | | Maximum | $4,339,565 | $4,453,745 | $3,986,063 | $4,945,730 | |
| | | Mean | $3,306,163 | $3,539,272 | $3,014,442 | $3,449,628 | |
| | | Median | $3,304,508 | $3,535,623 | $3,005,435 | $3,438,650 | |
| | | Standard Deviation | $293,945 | $316,086 | $269,230 | $335,887 | |
| | User | Minimum | $436,170 | $441,493 | $356,348 | $30,988 | Sensitivity analysis on simulations indicate the work zone capacity influences the user costs. Working hours is fixed from 8AM-5PM, work zone speed 40MPH, Work Zone Length 2 miles assumed constant in the risk analysis. |
| | | Maximum | $1,455,865 | $1,373,878 | $1,165,628 | $211,528 | |
| | | Mean | $961,021 | $968,780 | $797,151 | $133,207 | |
| | | Median | $968,145 | $974,660 | $807,326 | $135,484 | |
| | | Standard Deviation | $167,259 | $15,694 | $16,178 | $4,708 | |

Similarly, the results from probabilistic analysis approach are also included in Table 3.5. In all the analysis, Design 4 has the lowest user costs and Design 2 has the highest user and agency costs. The risk analysis approach results are also summarized in Figure 3.2 using relative cumulative probability graphs. At all probability levels, the designs have same relative positions. The results (Table 3.5 and Figure 3.2) can be used by decision-makers in selecting among alternative designs. Sensitivity analysis of various inputs and correlation coefficients of the main inputs have been included in Appendix B.

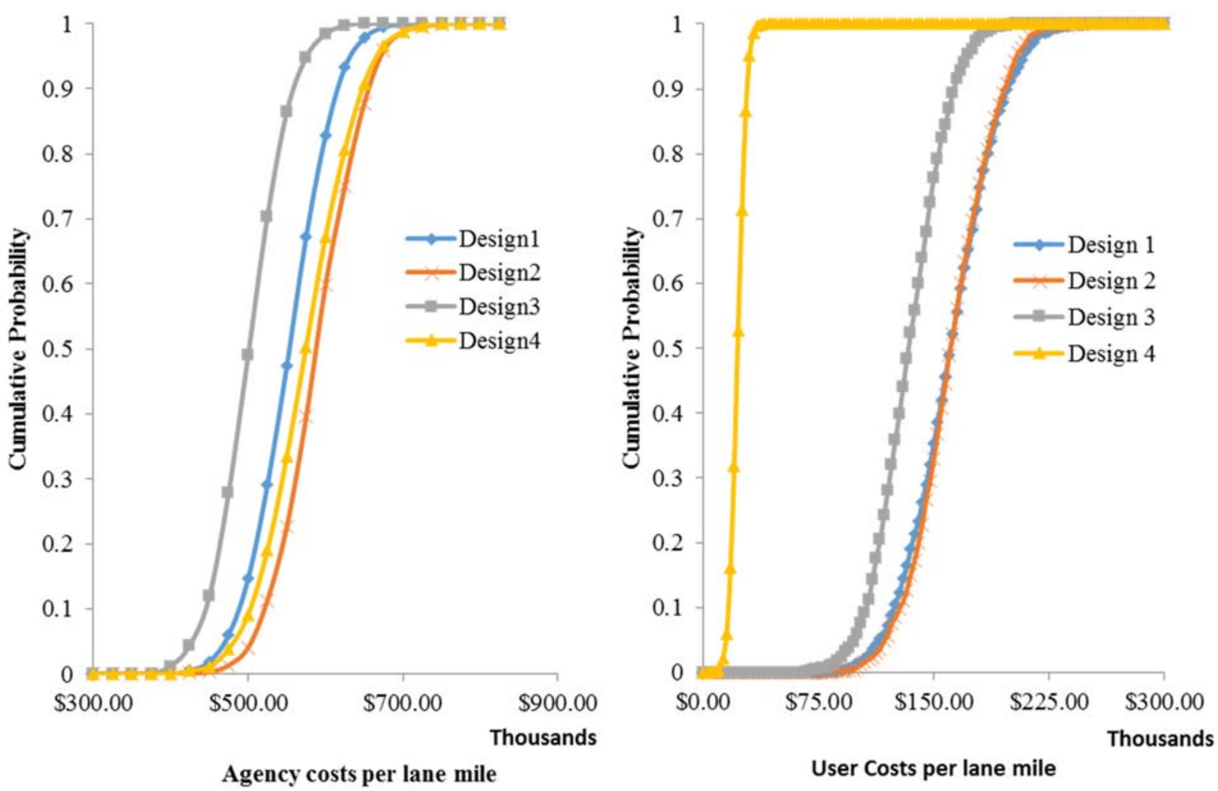



**Figure 3.2 Cumulative Probability Distribution of Agency Costs and User Costs**

### 3.3. Life Cycle Assessments of Environment Impacts

The Life Cycle Assessment (LCA-E) is a tool that comprehensively quantifies environmental impacts throughout the life cycle of a highway and includes components such as raw material extraction, processing, transportation and construction, traffic delays, use of

highways, deconstruction, disposal, etc. Although LCA-E tool is still developing, it has been utilized by some researchers (Santero, Masanet, and Horvath 2011a) for pavement evaluation for over a decade and the LCA steps for regular pavement life cycle evaluation are shown in Figure 3.3.

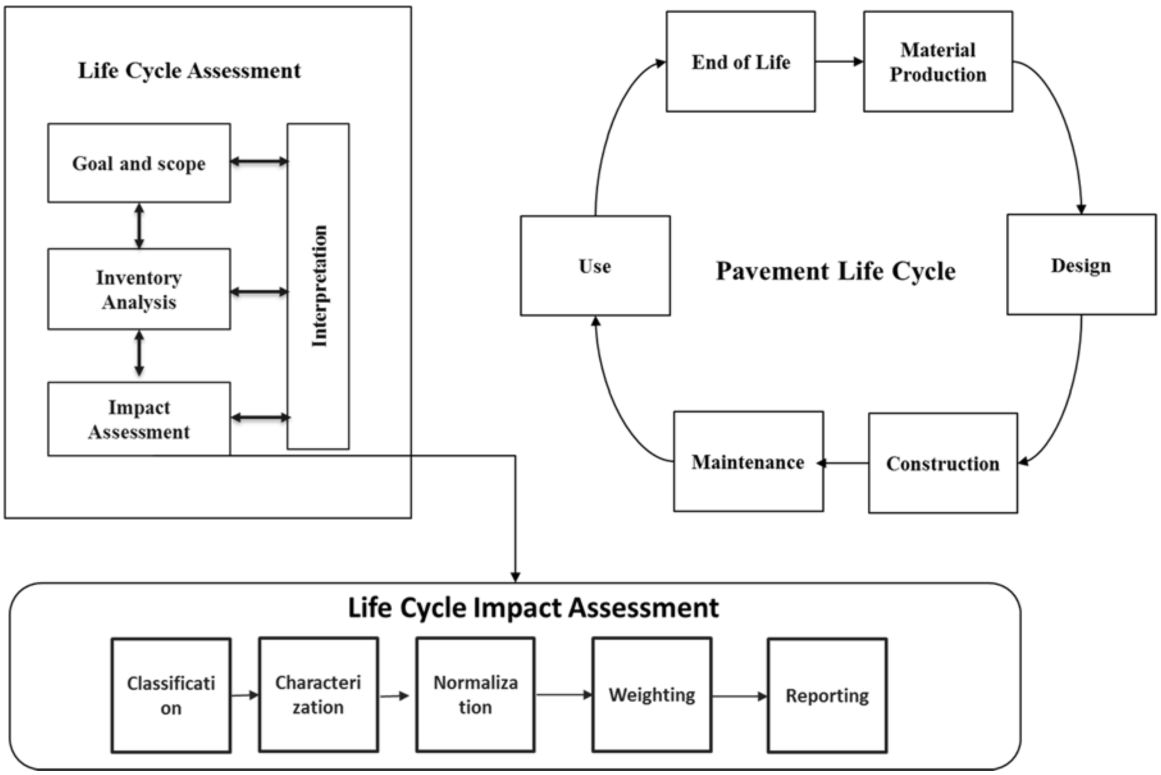



**Figure 3.3 Framework for LCA and Pavement Life Cycle**

According to Van Dam et al. (2015), "*The first phase of an LCA determines key features of the analysis including the depth and the breadth of an LCA, which can differ considerably depending on the overall goal. The scope of an LCA defines the system boundary of analysis (essentially, what life-cycle stages and processes are included in the LCA), the geographic and temporal boundaries of analysis, the functional unit of analysis, and also determines the required quality of data. Again, all of these depend on the subject and the intended use of the LCA.*" Based on the goal and scope, data needs to be collected in inventory analysis step which is also referred as Life Cycle Inventory (LCI) level. The inventory data is then modeled into impacts in impact

assessment phase, which is often referred as Life Cycle Impact Assessment (LCIA). There are various steps involved in LCIA namely: classification, characterization, normalization, and weighting.

### 3.3.1. Goal and Scope

For this study, the goal of conducting LCA-E is to evaluate the environmental impact of four pavement designs and the study is limited to the phases and activities that help in the differentiating environmental impact of the designs (scope). In Figure 3.4, the scope of the present study and models used for life cycle inventory (LCI) are displayed. Use phase, end of life phase, and equipment manufacture emissions were not included in this study. There are no well-established models that can assess the emissions depending on pavement surface type during the use phase. Even though rolling resistance was used by Santero et al. (2011b), it is difficult to account for the uncertainty in the predicting models. Hence use phase is ignored in this study. Although the end of life poses a unique burden on the environment especially for high volume highways, there is no clearly end of life where the pavement would be removed and thrown away (Weiland and Muench 2010). Thus it was not considered in this study. Also emission due to the manufacturing of construction equipment was not considered because the construction equipment have a substantial life and its environmental impact for a particular project will be minimal, thus, ignored. Additionally, allocating the manufacturing of construction equipment emission for a particular project cannot be performed due to non-availability of machinery data.

### 3.3.2. Life Cycle Inventory

Life cycle inventory (LCI) is a laborious process and needs numerous inputs. There are various LCI databases about pavements available in the US for estimating the LCI, namely Gabi, SimaPro, Athena, and PE-2, etc. Also the United States Environmental Protection Agency (US EPA) developed other LCI models which can be customized for LCA of pavements like, the Greenhouse Gases (GHG), Regulated Emissions, and Energy Use in Transportation Model (GREET), Motor Vehicle Emission Simulator (MOVES), NONROAD2008 model, etc. However,

FHWA has not reviewed and endorsed any LCI database currently available (U.S. Department of Transportation, Federal Highway Administration 2014). In practice, a complete LCA-E for pavements demands use of more than one LCI database due to the differences in the level of details in each database. Inventory analysis should include various pollutants emitted and energy usage of a pavement throughout its life.

In this study, various inventory models (Figure 3.4) were selected based on the reliability of emission data and feasibility to employ in pavement LCA-E and are discussed in the following paragraphs.

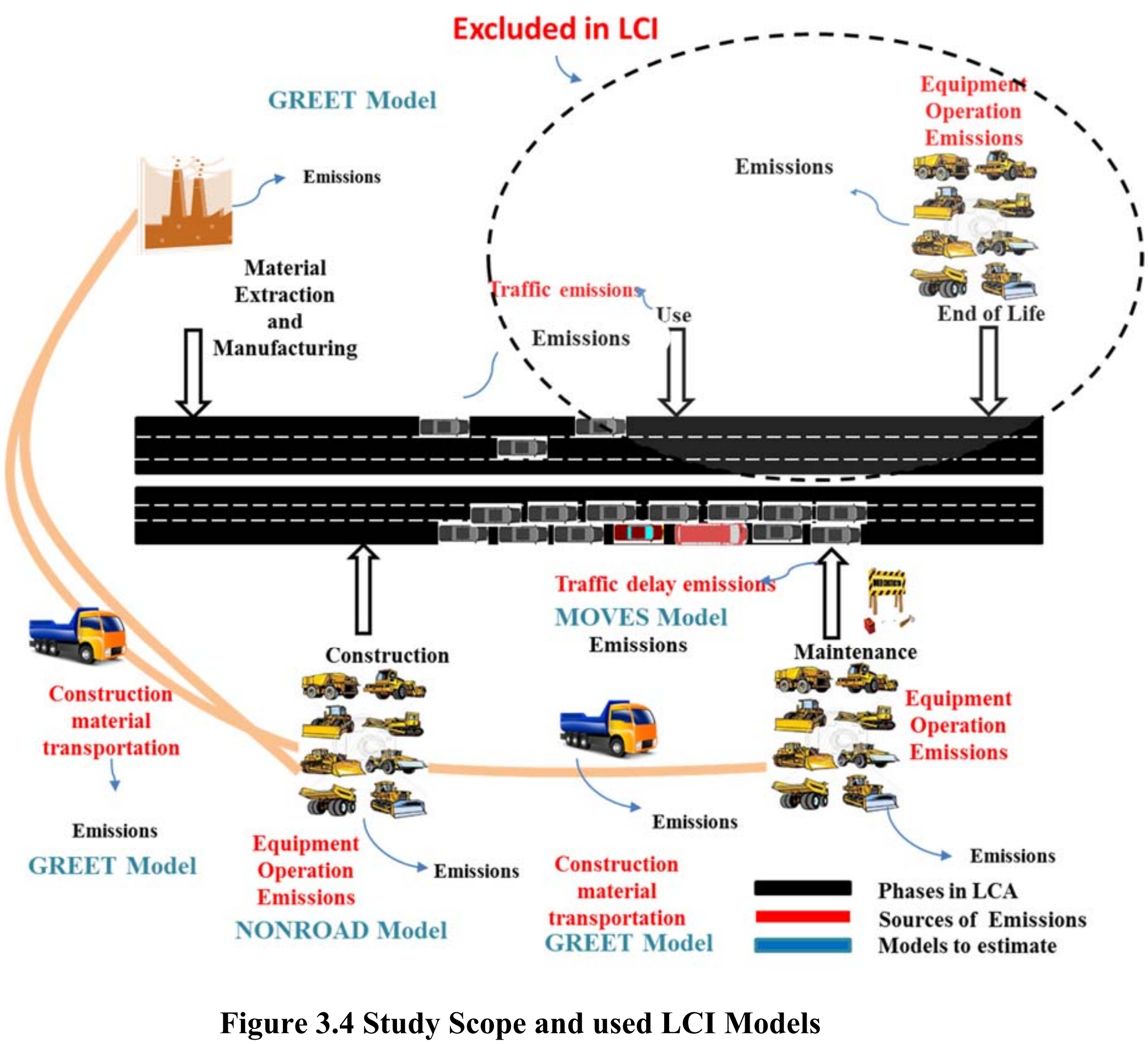



**Figure 3.4 Study Scope and used LCI Models**

#### *3.3.2.1. Material Extraction, Manufacturing, and Transportation Emissions Estimation*

In this study, a process approach LCA-E was employed to account for different emissions during material extraction and manufacturing, transportation, and construction of alternative pavement designs. In process approach, the inputs and emissions for each discrete process within a life cycle system boundary are quantified rather than reference values obtained from the published literature. For instance, one can find the LCI for fabricating of $yd^3$ of PCC through published literature, but it may not be accurate for LCA-E because LCI of PCC fabrication depends on various factors like mix design, logistics of raw material transportation, power usage, etc., which varies from one project to another one. In the end, total life cycle inputs, emissions, and impacts are estimated by summing up the data across all the discrete processes. For instance, the efforts placed in estimating inventory for every activity is exemplified through the LCI for PCC production and transportation as shown in Figure 3.5

The GREET model was used for emissions calculation (extraction, manufacture, and transportation) of all materials because it includes numerous fuel pathways and can be customized as per the requirements. For example, emissions data, due to electricity production, needed for cement production was available in GREET model as a national average. For this study, the emission data was modified based on the electricity generation mix of Texas ("Annual Energy Review - Energy Information Administration" 2015). The inventory emissions for electricity production in Texas is shown in Figure 3.6. Also an electricity distribution loss of 7.2% was considered in the study (Technology Options for the Near and Long Term 2003).

Energy consumption and air emissions for manufacturing of cement, diesel, natural gas and steel were selected as the per the US average values provided in GREET model. The other main source of emissions is the transportation of raw and processed materials to required locations,

which were also modelled using GREET model. In this study, a 20-ton capacity truck with full front haul and empty backhaul is assumed with fuel (diesel) consumption of 5.3 miles/ gallon for estimating emissions during transportation. Diesel is considered as the fuel used in trucks for transporting materials, which also includes upstream analysis of diesel used for trucks. An upstream emission considers the energy expended and emissions released for producing materials. Processes like PCC mixing and aggregate crushing were not available in GREET model. Therefore, these processes were added based on the field data (Marceau et al. 2007) and for aggregate crushing from GHG Inventory of CEMEX Jesse Morrow Mountain Plant (ENVIRON International Corporation San Francisco 2009). The hauling distances of 50 miles were assumed as displayed in Figure 3.5. The air emissions and energy consumed for production of 1 kg of PCC and transporting to the site are shown in Table 3.6.

#### *3.3.2.1. Equipment and Machinery Emissions Estimation during Construction*

The emissions from equipment and machinery, during construction, were estimated using NONROAD 2008 database that has emission data for equipment and machinery used in various sectors like construction, agriculture, etc. The critical step was matching the equipment required for construction with the equipment available in the database. If there is no equipment in the construction sector of NONROAD 2008, then the data is taken from equipment available in other sectors with similar horsepower (e.g. Road sweeper in Table 3.7).

The equipment needed for each activity were initially recorded during the cost estimates of each material in LCCA. The equipment details like horse power were taken from standard construction equipment manufacturers like Caterpillar, Dynapac, etc. Estimation of emissions for placing AC layer of Design 1 is shown in Table 3.7. After estimating the emissions from each equipment per hour, the total impacts is calculated by multiplying machinery hours required for activity (i.e., AC) and time efficiency.

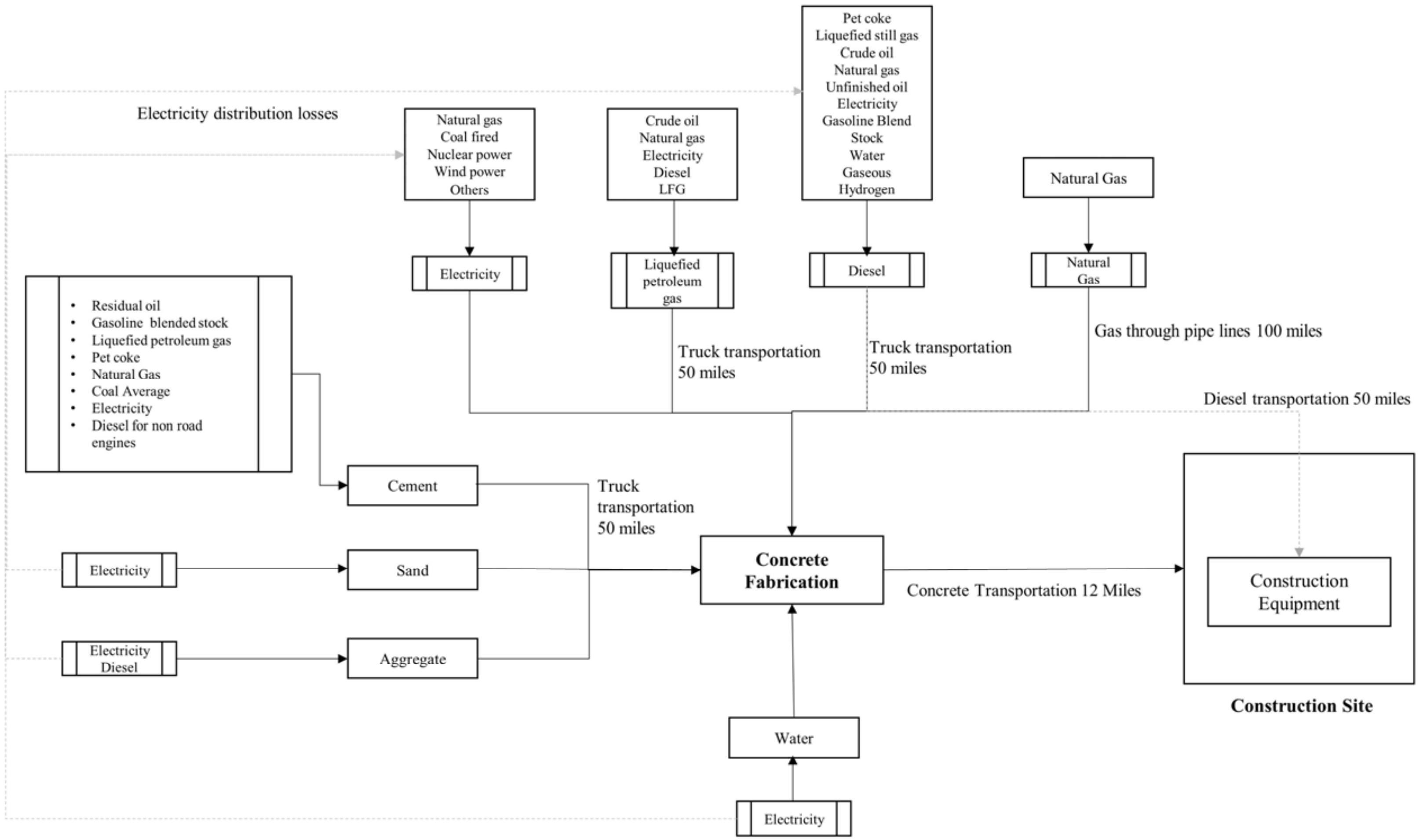
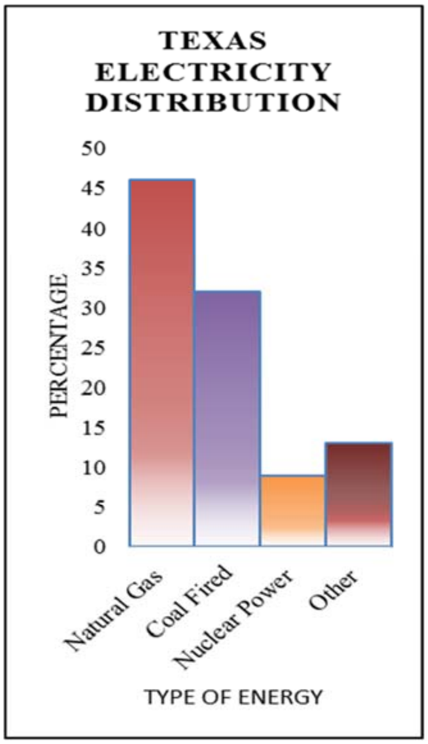



**Figure 3.5 Life Cycle Inventory for Concrete Production and Transportation.**




| Input or Output | Description | Amount |
|---|---|---|
| Energy Consumed (BTU/MMBTU) | Fossil Fuel | 1.39E+11 |
| | Natural Gas Fuel | 2.26E+06 |
| | Petroleum Fuel | 2.38E+04 |
| | Coal Fuel | 9.42E+03 |
| | Non Fossil Fuel | 3.39E+03 |
| | Nuclear Energy | 1.37E+03 |
| | Renewable | 1.40E+05 |
| | Biomass | 9.40E+01 |
| Air Emissions (g/MMBTU) | VOC | 1.93E+01 |
| | CO | 5.86E+01 |
| | $NO_x$ | 1.88E+02 |
| | $PM_{10}$ | 3.94E+01 |
| | $PM_{2.5}$ | 2.34E+01 |
| | $SO_x$ | 3.46E+02 |
| | $CH_4$ | 3.69E+02 |
| | $N_2O$ | 1.76E+00 |
| | $CO_2$ | 1.72E+05 |

**Figure 3.6 Emissions Inventory for Electricity Production in Texas (as per 2014)**

Note : VOC : Volatile Organic Compounds, CO : Carbon monoxide, $NO_x$ : Oxides of Nitrogen, $PM_{10}$ : Particle matter 10 micrometers or less in diameter, $PM_{2.5}$: Particle matter 2.5 micrometers or less in diameter, $SO_x$ : Oxides of Sulphur, $CH_4$ : Methane, $N_2O$ : Nitrous oxide, $CO_2$ : Carbon dioxide , $SO_2$ : Sulphur dioxide, $NH_3$ : Ammonia. BTU: British thermal unit, MM BTU: One million British Thermal Units

**Table 3.6 Emissions Inventory for Production and Transportation of Concrete**

| Air Emissions | Emissions For Concrete 1 kg | |
|---|---|---|
| | Materials Extraction | Transportation |
| VOC (grams) | 0.0154 | 0.0102 |
| CO (grams) | 0.2669 | 0.0374 |
| NOx (grams) | 0.5575 | 0.1316 |
| $PM_{10}$ (grams) | 0.0864 | 0.0067 |
| $PM_{2.5}$ (grams) | 0.0250 | 0.0057 |
| $SO_x$ (grams) | 0.5576 | 0.0035 |
| $CH_4$ (grams) | 0.1183 | 0.0218 |
| $N_2O$ (grams) | 0.0009 | 0.0000 |
| $CO_2$ (grams) | 376.93 | 24.53 |
| $SO_2$ (grams) | 0.0358 | 0.0004 |
| Energy Consumption (BTU) | 10498 | 202 |

Table 3.7 Estimation of Emissions from Construction Equipment Used in Construction of AC Layer

| Equipment | Equipment Model | Horse Power (HP) | Time Efficiency | NON ROAD MATCHING | | | RUNNING EXHAUSTS (grams/hour) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Sector | Equipment | Horse Power (HP) | Total Gaseous Hydrocarbons | CO | $NO_x$ | $NH_3$ | $SO_2$ | $CO_2$ | Brake Specific Fuel Consumption | $PM_{10}$ | $PM_{2.5}$ |
| 1 Asphalt Paver 130 HP | CAT AP555E | 142 | 0.75 | Construction | Paver | 100<hp<=175 | 30 | 141 | 350 | 0.59 | 0.44 | 72164 | 22651 | 32.11 | 31.15 |
| 1 Tandem Roller 10 Ton | BOMAG BW 161 ADO-5 | 138 | 0.75 | Construction | Rollers | 100<hp<=175 | 31 | 143 | 362 | 0.58 | 0.44 | 70873 | 22247 | 32.06 | 31.10 |
| 1 Roller Pneumatic Wheel 12 Ton | CAT CW 34 | 133 | 0.75 | Construction | Rollers | 100<hp<=175 | 31 | 143 | 362 | 0.58 | 0.44 | 70873 | 22247 | 32.06 | 31.10 |
| 1 Road Sweeper, 8" wide | ROADTECH FB-100 | 100 | 0.75 | Sector 3 | Sweepers/Scrubbers | 75<hp<=100 | 11 | 25 | 30 | 0.39 | 0.23 | 48293 | 15150 | 1.45 | 1.41 |
| 1 Pavement Profiler 750 HP | ROADTECH RX-700e/ex | 755 | 0.75 | Construction | Surfacing Equipment | 600<hp<=750 | 113 | 645 | 1076 | 3.11 | 2.07 | 382670 | 120070 | 66.72 | 64.71 |
| 1 F.E Loader W.M. 1.5 CY | CAT 908H2 | 69 | 0.75 | Construction | Tractors/Loaders/Backhoes | 50<hp<=75 | 20 | 130 | 219 | 0.35 | 0.24 | 43408 | 13627 | 14.50 | 14.07 |

#### *3.3.2.2. Emission Estimation during Scheduled Maintenance*

The three primary sources of emissions during maintenance of pavements are:

1. Emissions due to extraction, manufacturing, and transportation of raw materials required for maintenance (estimated as explained in the section "Material Extraction, Manufacturing, and Transportation Emissions Estimation").
2. Emissions from the construction equipment and machinery (calculated as described in the section "Equipment and Machinery Emissions Estimation during Construction").
3. Emissions from on-road vehicles due to traffic delays caused by maintenance operations performed within service life of pavement. A detailed procedure for estimating traffic delay emissions is included in Appendix C.

The emission inventory across various phases of pavement life cycle are presented in Table 3.8, which includes ten air emission pollutants and energy consumption.

### 3.3.3. Life Cycle Impact Assessment (LCIA)

LCIA is the final step in LCA-E. The ISO 14044 (2006) defines LCIA as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product (i.e. pavement) system". In LCIA, the influence of various pollutants (inventory data) on the environment can be demonstrated by converting them into impact categories. For example, Global Warming Potential (GWP) represents a particular environmental concern of climate change. Impact category amounts can be used to compare alternative designs (Weiland and Muench 2010). LCIA comprises of four components: classification, characterization, normalization, and weighting. Classification and characterization

**Table 3.8 Life Cycle Inventory of Four Pavement Designs (per Mile Length)**

| Air Emissions | Material Extraction and Manufacturing Phase. | | | | Transportation Phase | | | | Construction Phase | | | | Additional Emissions due to Traffic Delays. | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | D1 | D2 | D3 | D4 | D1 | D2 | D3 | D4 | D1 | D2 | D3 | D4 | D1 | D2 | D3 | D4 |
| VOC | 0.9 | 0.8 | 0.7 | 2.4 | 0.9 | 0.6 | 0.6 | 0.4 | | | | | 2.6 | 2.6 | 2.3 | 0.2 |
| CO | 11.8 | 6.8 | 7.0 | 23.7 | 3.5 | 2.0 | 2.1 | 1.5 | 0.2 | 0.7 | 0.7 | 0.2 | 71.2 | 71.2 | 66.1 | 7.3 |
| $NO_x$ | 42.7 | 20.9 | 22.9 | 18.2 | 12.2 | 7.2 | 7.3 | 5.4 | 0.7 | 1.6 | 1.6 | 0.5 | 29.4 | 29.4 | 26.8 | 3.4 |
| $PM_{10}$ | 3.9 | 2.2 | 2.3 | 3.6 | 0.6 | 0.4 | 0.4 | 0.3 | 0.0 | 0.1 | 0.1 | 0.0 | 1.3 | 1.3 | 1.1 | 0.1 |
| $PM_{2.5}$ | 0.1 | 0.3 | 0.3 | 1.2 | 0.5 | 0.3 | 0.3 | 0.2 | 0.0 | 0.1 | 0.1 | 0.0 | 1.2 | 1.2 | 1.0 | 0.1 |
| $SO_x$ | 5.1 | 3.1 | 3.1 | 21.1 | 0.3 | 0.2 | 0.2 | 0.1 | | | | | | | | |
| $CH_4$ | 19.8 | 13.1 | 12.2 | 6.6 | 2.0 | 1.2 | 1.2 | 0.9 | | | | | 0.5 | 0.5 | 0.5 | 0.1 |
| $N_2O$ | 0.5 | 0.4 | 0.4 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | | | | | 0.0 | 0.0 | 0.0 | 0.0 |
| $CO_2$ | 3307 | 2597 | 2423 | 11789 | 1999 | 1088 | 1142 | 887 | 147 | 284 | 284 | 92 | 46283 | 46283 | 45248 | 8777 |
| $SO_2$ | 5.0 | 2.4 | 2.7 | 1.3 | 0.0 | 0.0 | 0.0 | 0.0 | | | 0.0 | | 0.17 | 0.2 | 0.2 | 0.0 |
| Energy Consumption. | 1.6E+11 | 1.0E+11 | 9.6E+10 | 2.8E+11 | 1.1E+10 | 5.1E+9 | 5.6E+9 | 5.5E+9 | 1700 | 3600 | 3600 | 3600 | 267465 | 267465 | 269268 | 49572 |

steps are prescribed for use in LCIA, while normalization and weighting are considered optional due to subjectivity associated with them. Although proposed, most of the previous LCA-E pavement case studies remained ay the stage of performing inventory analysis (Classification) and few characterized the inventory into impact categories (Characterization).

#### *3.3.3.1. Classification*

In this inventory step, pollutants are assigned to relevant impact categories. For instance, carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), etc., contribute to GWP impact group. Similarly, the other pollutants are classified based on the impact category. Table 3.9 displays the classification of various impact categories namely: GWP, Eutrophication (EUT), Smog (SMOG), Acidification (ACID), and Human Health Criteria Air Pollutants (HHCR).

#### *3.3.3.2. Characterization*

In characterization step, various pollutants are converted to a standard impact category and the factors required to transform the emissions are called characterization factors (Table 3.9). These conversion factors were provided by the EPA's impact assessment Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI), which strives in attaining consistency in environmental decision-making. Table 3.9 shows the characterized data of selected impact categories.

#### *3.3.3.1. Normalization*

It is essential for decision makers to understand the real sense of the characterized impacts on inventoried emissions. Since the decision makers use these one or two numbers in selecting a design. The aggregated impact categories are not easy to interpret in every aspect. Each impact category differs in their units and environment impacts. They may not directly correspond to future environmental problems or existing hazards (Sleeswijk et al. 2008). The absolute importance of an aggregated impact category is hard to interpret, until unless it is not placed in an adequate environment context (Sleeswijk et al. 2008) and normalization aims at addressing this issue.

**Table 3.9 Characterization Factors for Impact Categories and Characterized Impacts**

| Classification and Characterization Factors[1] | | | | | |
|---|---|---|---|---|---|
| | **GWP kg CO2-eq/kg** | **EUT kg N-eq/kg** | **SMOG kg Nox-eq/kg** | **ACID kg H+eg/kg** | **HHCR kg milli-DALYS/kg** |
| **VOC** | | | 3.595 | | |
| **CO** | | | 0.056 | | 0.00036 |
| **Nox** | | 0.044 | 24.793 | 0.700 | 0.007 |
| **PM10** | | | | | 0.228 |
| **PM2.5** | | | | | 1 |
| **Sox** | | | | 1 | |
| **CH4** | 25 | | 0.0144 | | |
| **N2O** | 298 | | | | |
| **CO2** | 1 | | | | |
| **SO2** | | | | 1 | 0.061 |
| **Characterized Impacts** | | | | | |
| | **GWP CO2e in Tons** | **EUT N in tons** | **SMOG Nox-in tons** | **ACID H+ in tons** | **HHCR in tons** |
| **Design 1** | 52362.32 | 0.36 | 89.69 | 3675.99 | 0.95 |
| **Design 2** | 50698.79 | 0.25 | 63.36 | 2534.05 | 0.74 |
| **Design 3** | 49505.57 | 0.25 | 62.42 | 2511.80 | 0.69 |
| **Design 4** | 21782.36 | 0.12 | 30.42 | 2180.83 | 0.62 |
| **Normalization Factors** (Ryberg et al. 2013) | | | | | |
| | **GWP kg CO2-eq/kg** | **EUT kg N-eq/kg** | **SMOG kg Nox-eq/kg** | **ACID kg H+eg/kg** | **HHCR kg milli-DALYS/kg** |
| **Impact Per Person Year in US 2008** | 24000 | 22 | 1400 | 91 | 24 |
| **Normalized Impact Categories (Persons Equivalent)** | | | | | |
| | **GWP** | **EUT** | **SMOG** | **ACID** | **HHCR** |
| **Design 1** | 1982 | 155 | 1378 | 698 | 160 |
| **Design 2** | 1918 | 108 | 962 | 471 | 132 |
| **Design 3** | 1873 | 107 | 952 | 470 | 121 |
| **Design 4** | 824 | 50 | 451 | 417 | 106 |

Normalization relates the magnitude of the calculated impact scores to a common reference, putting the impact scores in relation to the impact of society's production/consumption activities, thereby, gaining a better understanding of the contribution of the product system under study to each impact score in relation to those of the reference system (Ryberg et al. 2013). The reference system used for normalization should be appropriate and both temporally and spatially representing the boundaries of the life cycle of the product or system being studied, as well as being sufficiently broad and complete.

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[1] Characterization factors were taken from TRACI

The drawback of disregarding the normalization step in the LCIA are: decision-makers will be inclined to their first impressions, may place unnecessary importance on insignificant data, and may make inappropriate choices based on their assumptions without clearly understanding the numbers (Rogers and Seager 2009). Ultimately, all the efforts in conducting LCA-E will be down the drain if the decision-makers select an unsustainable design.

In this study, the characterized impact category data is further normalized using the Updated US normalization factors for TRACI 2.1 (Ryberg et al. 2013) as shown in Table 3.9. In this study, the energy consumption is not characterized by fossil fuel depletion and normalized due to the non-availability of specific fuel consumption within energy consumption. However, to understand the magnitude of energy consumption in LCA-E, the energy consumption is compared with the US Transportation sector energy consumption of 2014 ("Annual Energy Review - Energy Information Administration" 2015).

#### *3.3.3.2. Weighting*

The weightings of various impact categories were assigned in this step. In this study, the weightings for different impact categories were developed based on the judgments from various experts through the Analytic Hierarchy Method (AHP). The procedure adopted for establishing weights were similar to the steps explained in the section "Sustainable Decision-Making."

Detailed explanation of LCIA is included in Appendix D (An approach for performing Life Cycle Impact Assessment of pavements for evaluating alternative pavement designs)

Similarly, a new method for normalization and weighting is proposed and is included in Appendix E (Enhancing pavement design selection by incorporating normalization into life cycle impact assessments). Various normalization methods their merits and demerits are also discussed in this paper.

## 3.4. Life Cycle Assessments of Social Impacts (LCA-S) of Pavements

Social Life Cycle Assessment (LCA-S) of pavements is a technique that aims to assess the social impacts of pavement along its life cycle. It is still at a nascent stage, and there does not yet

exist a comprehensive framework for performing it in pavements, many researchers suggest a framework similar to LCA-E. However, social and environment impacts are considerably different in their characteristics. Environmental impacts are often considered as impacts on either local, regional, or global areas and always are negative in nature. Whereas social impacts are on various stakeholders (shareholders, owners, employees, labor, local community, global community). Pavements have positive as well as negative influences on people. Hence, one of the key distinguishing points in LCA-S compared with LCA-E is stakeholder management. Upon comprehensive literature review, this study proposed a framework for conducting LCA-S in construction as shown in Figure 3.7.Complete details of the literature reviewed are included in Appendix F (Feasibility evaluation of social life cycle assessment inclusion in pavements)

Since the goal of the dissertation is a selection of sustainable pavement structure, it is necessary to include social pillar of sustainability as well. Irrespective of the pavement structure there are some social impacts remain constant like the migration of people, education of local communities, disruption in local social behaviors, land required for construction, etc. Due to complexity and unavailability of the data, the impact of such issues was not considered in this study.

Various social impacts are sole because of pavement type like noise, accidents, discomfort to the public due to construction, urban heat island effect, etc. Traffic noise is considered in this study as a social indicator because traffic noise has an acute impact on human health and leading factor for noise emission is tire pavement interaction. Since the designs considered in the present study have different surface properties, the traffic noise emitted can be used as a parameter to distinguish the pavements. Additionally, the data is available to assess the noise level. Therefore, noise, as a social indicator was considered for this study and the details are included in Appendix G (Noise as a social impact indicator for selection of sustainable pavements).

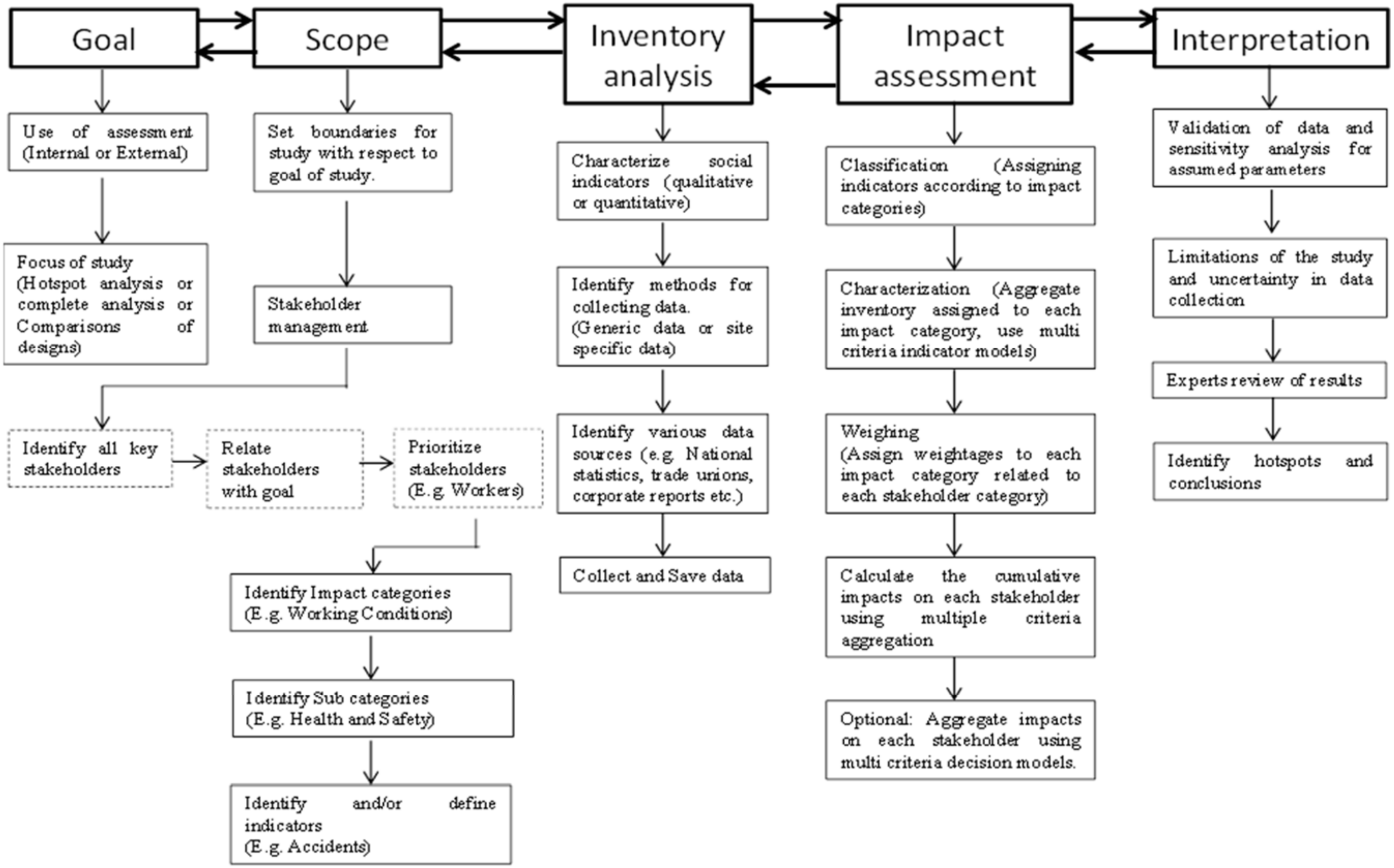


**Figure 3.7 Proposed Approach for Social Life Cycle Assessment**

**Table 3.10 Outline of Parameters Considered for SLCA of Pavements**

| Phase | Parameters | Description |
|---|---|---|
| Goal | Use of assessment | Internal (decision makers), Comparisons of pavement structure designs. |
| | Theme | Human health and well being |
| Scope | Boundary | Use phase |
| | Stakeholders | Local community |
| | Impact category | Human health |
| | Indicator | Traffic Noise |
| Inventory analysis | Method | Assessment of traffic noise levels during use phase of pavement for 30 years using (TNM2.5) |
| Impact assessment | Impact Pathway | No established pathway between noise levels and human health. FHWA recommendation for noise levels is used as thresholds for further assessment. |
| | Characterization | Noise impacts are calculated as costs and emissions arise due to mitigation of traffic noise *i.e.* to keep noise less than threshold as recommended by FHWA. |
| Interpretation | Limitations | TNM will not consider the deterioration of pavement surface performance with time. Noise emissions during construction and maintenance are not considered. |

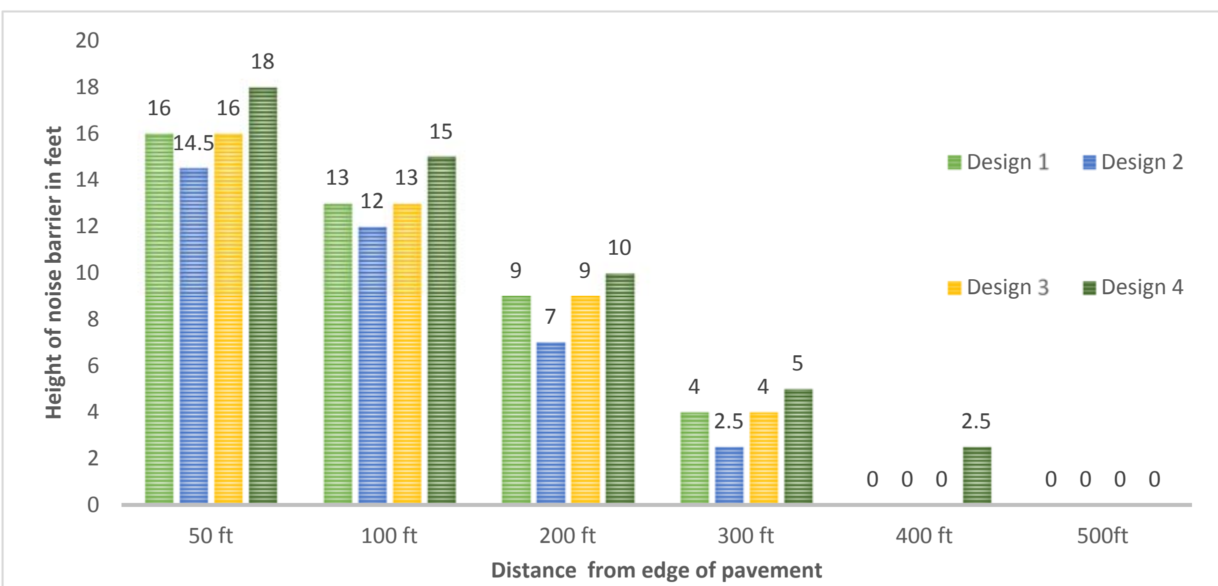


**Figure 3.8 Height of Noise Barrier Required for Dissipating Noise (below 67db)**

**Table 3.11 Environmental Impacts and Life Cycle Costs due to Construction of Noise Barrier Wall**

| Impact | Distance in feet from pavement | Designs | | | | Designs | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | D1 | D2 | D3 | D4 | D1 | D2 | D3 | D4 |
| | | Impacts | | | | Normalized Impacts (Equivalent Cars) | | | |
| Global Warming Potential | 50 | 893.48 | 810.38 | 893.48 | 1004.29 | 183.51 | 166.45 | 183.51 | 206.27 |
| | 100 | 727.27 | 671.87 | 727.27 | 838.08 | 149.38 | 138.00 | 149.38 | 172.14 |
| | 200 | 505.66 | 394.85 | 505.66 | 561.06 | 103.86 | 81.10 | 103.86 | 115.24 |
| | 300 | 228.64 | 145.53 | 228.64 | 284.04 | 46.96 | 29.89 | 46.96 | 58.34 |
| | 400 | 0.00 | 0.00 | 0.00 | 145.53 | 0.00 | 0.00 | 0.00 | 29.89 |
| Eutrophication | 50 | 0.07 | 0.06 | 0.07 | 0.07 | 161.61 | 146.57 | 161.61 | 181.66 |
| | 100 | 0.05 | 0.05 | 0.05 | 0.06 | 131.53 | 121.50 | 131.53 | 151.58 |
| | 200 | 0.04 | 0.02 | 0.01 | 0.02 | 91.42 | 71.36 | 91.42 | 101.45 |
| | 300 | 0.02 | 0.00 | 0.00 | 0.00 | 41.28 | 26.24 | 41.28 | 51.31 |
| | 400 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 26.24 |
| Smog | 50 | 2.50 | 2.27 | 2.50 | 2.81 | 131.51 | 119.27 | 131.51 | 147.83 |
| | 100 | 2.04 | 1.88 | 2.04 | 2.35 | 107.04 | 98.88 | 107.04 | 123.35 |
| | 200 | 1.57 | 0.64 | 0.41 | 0.64 | 74.40 | 58.09 | 74.40 | 82.56 |
| | 300 | 0.80 | 0.00 | 0.00 | 0.00 | 33.61 | 21.38 | 33.61 | 41.77 |
| | 400 | 0.41 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 21.38 |
| Acidification | 50 | 2.50 | 2.27 | 2.50 | 2.81 | 390.10 | 353.85 | 390.10 | 438.42 |
| | 100 | 2.04 | 1.88 | 2.04 | 2.35 | 317.61 | 293.45 | 317.61 | 365.93 |
| | 200 | 1.42 | 1.11 | 1.42 | 1.57 | 220.96 | 172.63 | 220.96 | 245.12 |
| | 300 | 0.64 | 0.41 | 0.64 | 0.80 | 100.14 | 63.90 | 100.14 | 124.31 |
| | 400 | 0.00 | 0.00 | 0.00 | 0.41 | 0.00 | 0.00 | 0.00 | 63.90 |
| Human Health Criteria Air pollutants | 50 | 0.15 | 0.14 | 0.15 | 0.17 | 847.88 | 769.27 | 847.88 | 952.70 |
| | 100 | 0.12 | 0.11 | 0.12 | 0.14 | 690.65 | 638.24 | 690.65 | 795.47 |
| | 200 | 0.09 | 0.07 | 0.09 | 0.10 | 481.02 | 376.20 | 481.02 | 533.43 |
| | 300 | 0.04 | 0.03 | 0.04 | 0.05 | 218.97 | 140.36 | 218.97 | 271.38 |
| | 400 | 0.03 | 0.04 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 140.36 |
| Life Cycle Cost Analysis (present worth per mile in $) | 50 | $2,717,734 | $2,462,947 | $2,717,734 | $3,057,451 | | | | |
| | 100 | $2,208,159 | $2,038,301 | $2,208,159 | $2,547,876 | | | | |
| | 200 | $1,528,725 | $1,189,009 | $1,528,725 | $1,698,584 | | | | |
| | 300 | $679,434 | $424,646 | $679,434 | $849,292 | | | | |
| | 400 | $0 | $0 | $0 | $424,646 | | | | |

## 3.5. Sustainable Decision-Making

In this study, the decision modelling was developed to address two objectives

#### *3.5.1.1. Objective 1*

- To integrate multiple criteria involved in sustainability. This objective was achieved by using modified analytic hierarchy process (AHP), which is enhanced version of traditional AHP. A detailed description of proposed simplified method is included in Appendix H (Application of fuzzy preference analytic hierarchy process (AHP) logic in evaluating the sustainability of transportation infrastructure requiring multi-criteria decision-making).

#### *3.5.1.2. Objective 2*

- Since sustainability is interdisciplinary, experts involved in group decision should belong to different disciplines. Therefore, this study proposed a group decision model and submitted a manuscript for publication entitled "Integration of Data Envelopment Analysis (DEA) based preference aggregation method and α- PSO (Particle Swarm Optimization) technique into group decision model." This manuscript is placed in Appendix I. The purpose of the manuscript is to develop a decision-making process that requires minimal intervention and provides maximum to satisfaction to the decision makers by making sure that their input is relevant to the process.

For demonstrating decision-making process (objective 1), a panel of eight experts was formed. The panel was a heterogeneous group which comprised of people from academia and industry. Decision makers' expertise pool included construction management, research, highway construction, environmental, etc. Summary of data about LCCA (Table 3.5, Figure 3.2), LCA-E (Table 3.9), LCA-S (Table 3.11) for the four designs were tabulated in an Excel file along with the hierarchy of criteria (Figure 3.9). Each expert is expected to provide inputs (comparison of the relative significance of one design/criteria with other design/criteria for a defined

criteria/objective, the comparison is often called as "Pairwise Comparison" in AHP terminology) in four sheets namely criteria, economy, environment, and social.

Supporting data was provided in other sheets, such as the hierarchy of selection of pavement as shown in Figure 3.12, pairwise comparisons scale in Table 3.12, etc. The template was modified upon feedback from experts.

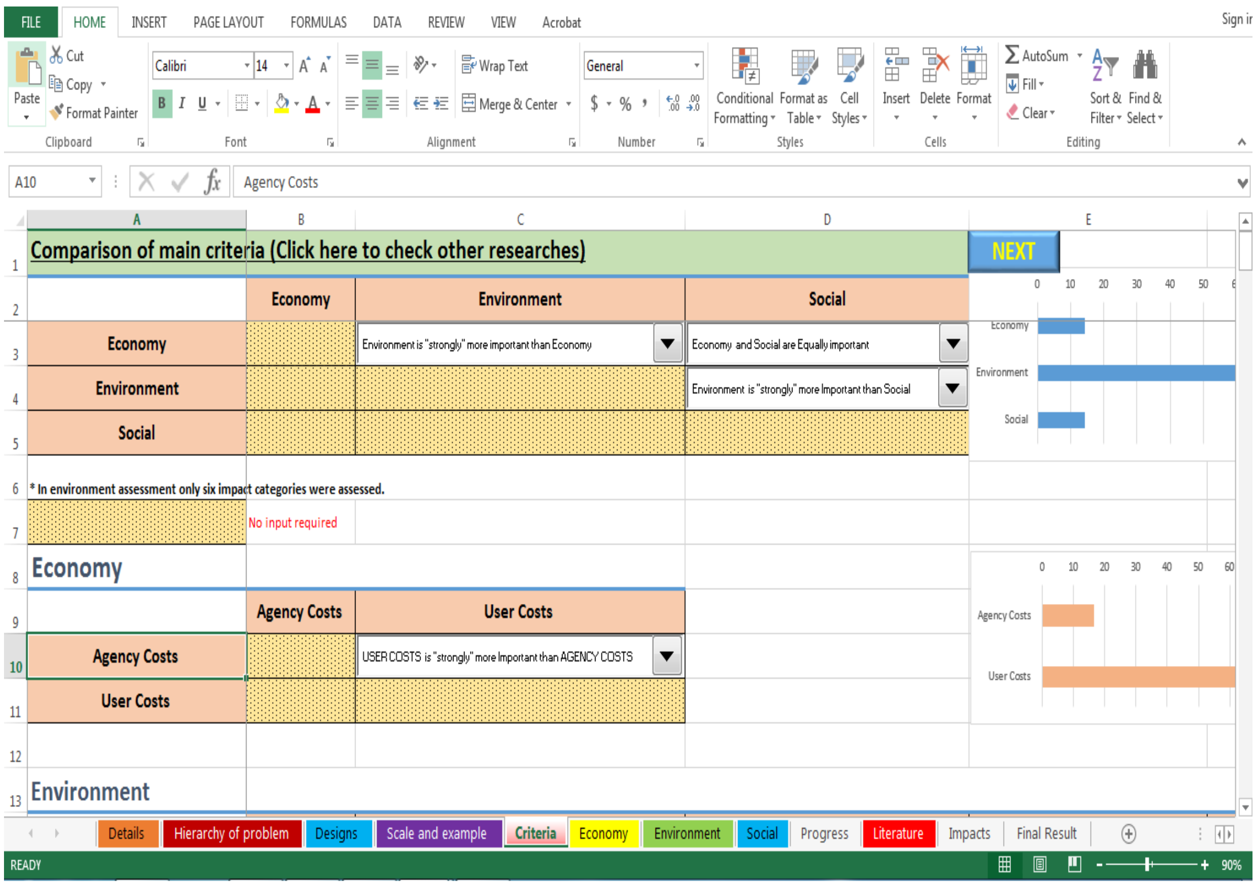


**Figure 3.9 Decision Template Developed for Assessment**

Each expert needs to provide one hundred pairwise comparisons for the selection of most preferred design in this study. One of the common criticism obtained from decision makers was the requirement of too many pairwise comparisons, which was expected. One more unnoticed problem by experts in AHP was inconsistency in expert's pairwise comparisons. For example, Figure 3.10 shows the pairwise comparisons for main criteria economy, environment and social.

**Table 3.12 Pairwise Comparison Scale Employed**

| Comparison Scale Description (Design1 vs Design 2) | Numerical Scale |
|---|---|
| D1 and D2 are Equally significant | 1 |
| D1 is Weakly significant than D2 | 3 |
| D1 is moderately significant than D2 | 5 |
| D1 is strongly significant than D2 | 7 |
| D1 is extremely significant than D2 | 9 |
| D2 is Weakly significant than D1 | 1/3 |
| D2 is moderately significant than D1 | 1/5 |
| D2 is strongly significant than D1 | 1/7 |
| D2 is extremely significant than D1 | 1/9 |

The pairwise comparison of economy vs. environment was given as "economy is strongly more important than environment"; environment vs. social was given as "social is strongly more important than environment". The two pairwise comparisons imply that economy and social were equally important. However the pairwise comparison (economy vs. social) was given as "economy was weakly important than social" which contradicts the above two choices. These pairwise comparisons yielded weights as 54%, 8%, and 38% for the economy, environment, and social criteria, respectively. Thus, inconsistency sneaks into decision-making in AHP and inconsistency are more pronounced if more pairwise comparisons are required. In general, inconsistency (measured as Consistency Ratio (CR)) up to 10% is acceptable in AHP and maintaining CR<10% is quite challenging.

An enhanced version of AHP was developed for this study to surmount the two problems in AHP, i.e., to reduce the number of pairwise comparisons (which needs around 50% of inputs than traditional AHP for this study) and to maintain consistency. For the same criterion illustrated in Figure 3.10, the proposed AHP yields the weighs of three criteria (economy, environment, and social) as 45%, 10%, and 45% as shown in Figure 3.11. Here the weights support the decision maker choices (economy, social are strongly important than environment and both economy, social have same weights).

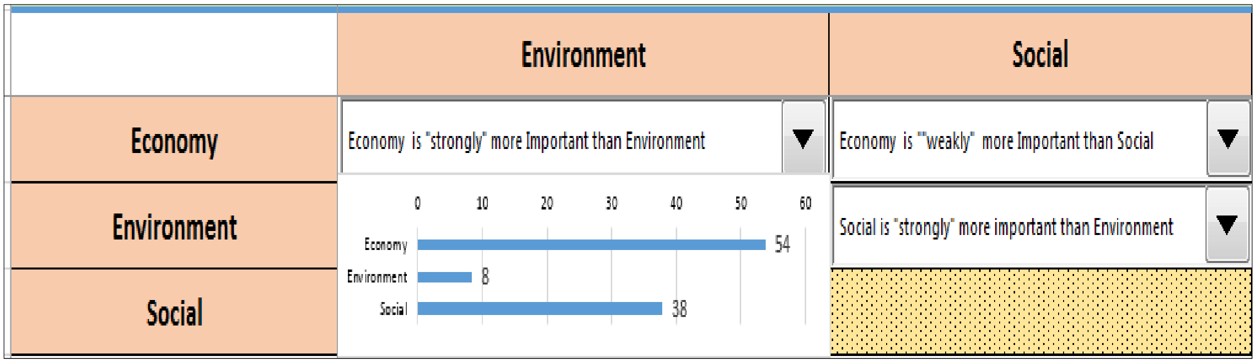


**Figure 3.10 An Illustration of Pairwise Comparisons of Criteria using Traditional AHP**

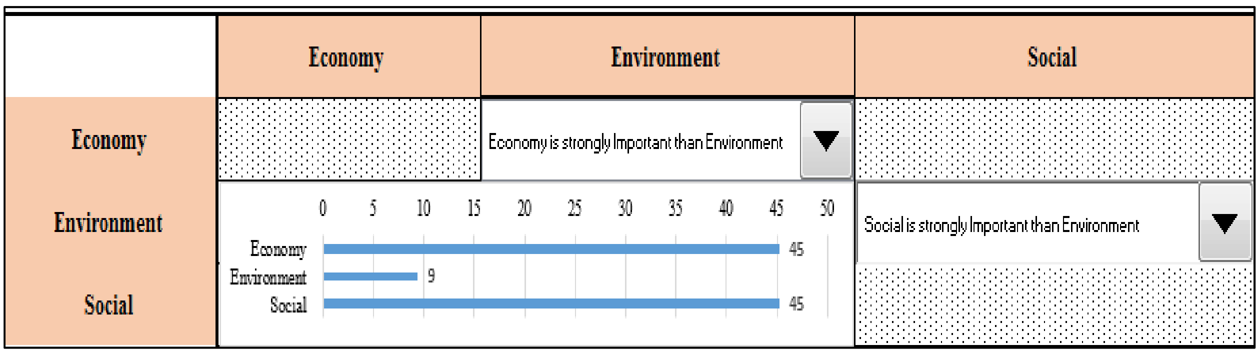


**Figure 3.11 An Illustration of Pairwise Comparisons of Criteria using Proposed AHP**

The developed model was not provided to decision makers for two reasons:

1. If two decision models were provided to decision makers, then more effort is required from them. There may be a possibility where decision makers might just fill the pairwise comparisons requirement rather than actual judging.
2. The data required for proposed AHP method is a subset of data required for traditional AHP. Hence, the data provided for traditional AHP can be used in the proposed method.

The concepts for developing the proposed AHP along with its usefulness is explained in detail with a numerical example in Appendix H.

The weights calculated for the criteria and sub-criteria, as shown in Figure 3.12, from both traditional and proposed AHP's are shown in the Table 3.13 and Table 3.14, respectively. The

weights for criteria/sub-criteria from both methods were different due to the reasons explained above.

The pairwise comparisons from experts were used to calculate the weights for each design for each criterion/sub-criterion. The weights calculated for each design across each alternative were added to get the final weightages. Rankings were assigned to each design based on their final weightages. The final weights for designs were calculated and tabulated in Table 3.15 (traditional AHP) and Table 3.16 (proposed AHP). Irrespective of the method employed, the more experts were in favor towards Design 4. Six out of eight experts chose Design 4 when weights were evaluated through traditional AHP, and five out eight experts chose Design 4 when proposed AHP was employed. The rankings for the four designs based on inputs from eight experts are shown in Figure 3.13. The differences between the rankings by both methods (traditional vs. proposed) were due to the inconsistency in pairwise comparisons in traditional AHP.

The next objective was to combine the individual expert's decisions into a group decision. A simple method is to average weights from all experts. But there are two problems associated with using an average.

1. Influence of outlier: The average can be biased towards an outlier. If any expert favors a particular design (product) and assigns a maximum weight to one design, the average will be likely directed by an outlier.
2. Failure to define a clear winner: The other problem often noticeable in averaging is a failure to yield a clear winner. This problem is not evident from this case study because Design 4 outshines other designs. For instance, if the decision has to be made among the first three designs, the average values for Design 1, 2 and 3 are 0.24, 0.23, 0.24 (Table 3.16), respectively. Averaging the weights did not yield a clear winner in this scenario.

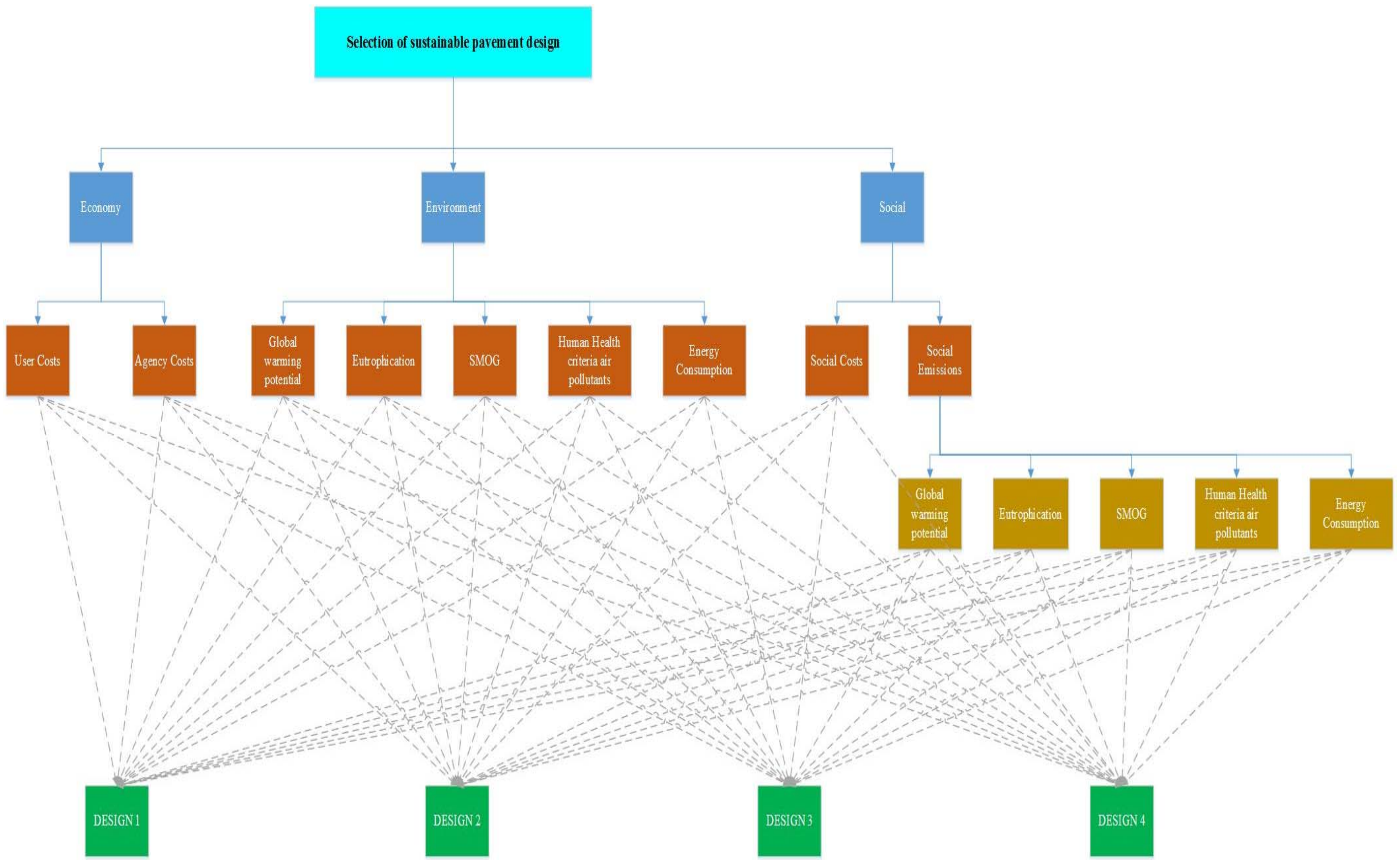


**Figure 3.12 Hierarchy of Criteria and Sub-Criteria for Selection of Sustainable Pavement Design**

**Table 3.13 Calculated Weightages for Criteria and Sub-criteria based on the Inputs from Decision Makers (Traditional AHP)**

| Comparing | Criteria/sub-criteria | Decision Maker (DM) weightages | | | | | | | | Average | Standard Deviation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DM1 | DM2 | DM3 | DM4 | DM5 | DM6 | DM7 | DM 8 | | |
| Main Criteria | Economy | 0.14 | 0.45 | 0.54 | 0.145 | 0.59 | 0.33 | 0.37 | 0.33 | 0.36 | 0.15 |
| | Environment | 0.43 | 0.09 | 0.08 | 0.71 | 0.33 | 0.33 | 0.47 | 0.33 | 0.35 | 0.19 |
| | Social | 0.43 | 0.45 | 0.38 | 0.145 | 0.08 | 0.33 | 0.16 | 0.33 | 0.29 | 0.13 |
| Subcriteria/ Economy | Agency Costs | 0.25 | 0.75 | 0.13 | 0.17 | 0.50 | 0.50 | 0.83 | 0.50 | 0.45 | 0.24 |
| | User Costs | 0.75 | 0.25 | 0.88 | 0.83 | 0.50 | 0.50 | 0.17 | 0.50 | 0.55 | 0.24 |
| Subcriteria/ Environment | GWP | 0.15 | 0.11 | 0.42 | 0.36 | 0.23 | 0.03 | 0.14 | 0.17 | 0.20 | 0.12 |
| | EUT | 0.14 | 0.04 | 0.03 | 0.07 | 0.03 | 0.14 | 0.14 | 0.17 | 0.09 | 0.05 |
| | SMOG | 0.24 | 0.15 | 0.20 | 0.07 | 0.25 | 0.29 | 0.25 | 0.17 | 0.20 | 0.07 |
| | ACID | 0.14 | 0.23 | 0.13 | 0.07 | 0.16 | 0.07 | 0.07 | 0.17 | 0.13 | 0.05 |
| | HHCR | 0.28 | 0.33 | 0.10 | 0.07 | 0.11 | 0.32 | 0.31 | 0.17 | 0.21 | 0.10 |
| | Energy Consumption | 0.05 | 0.15 | 0.12 | 0.36 | 0.22 | 0.15 | 0.09 | 0.17 | 0.16 | 0.09 |
| Subcriteria/Social | Social Costs | 0.50 | 0.25 | 0.83 | 0.17 | 0.17 | 0.50 | 0.83 | 0.50 | 0.47 | 0.25 |
| | Social Emissions | 0.50 | 0.75 | 0.17 | 0.83 | 0.83 | 0.50 | 0.17 | 0.50 | 0.53 | 0.25 |

**Table 3.14 Calculated Weightages for Criteria and Sub-criteria based on the Inputs from Decision Makers (Proposed AHP)**

| Comparing | Criteria/sub-criteria | Decision Maker (DM) weightages | | | | | | | | Average | Standard Deviation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DM1 | DM2 | DM3 | DM4 | DM5 | DM6 | DM7 | DM 8 | | |
| Main Criteria | Economy | 0.15 | 0.45 | 0.45 | 0.145 | 0.66 | 0.33 | 0.68 | 0.33 | 0.40 | 0.19 |
| | Environment | 0.42 | 0.09 | 0.09 | 0.71 | 0.29 | 0.33 | 0.26 | 0.33 | 0.32 | 0.18 |
| | Social | 0.42 | 0.45 | 0.45 | 0.145 | 0.05 | 0.33 | 0.06 | 0.33 | 0.28 | 0.16 |
| Subcriteria/ Economy | Agency Costs | 0.26 | 0.74 | 0.13 | 0.18 | 0.50 | 0.50 | 0.82 | 0.50 | 0.45 | 0.23 |
| | User Costs | 0.74 | 0.26 | 0.87 | 0.82 | 0.50 | 0.50 | 0.18 | 0.50 | 0.55 | 0.23 |
| Subcriteria/ Environment | GWP | 0.10 | 0.05 | 0.52 | 0.35 | 0.29 | 0.03 | 0.03 | 0.17 | 0.19 | 0.17 |
| | EUT | 0.10 | 0.02 | 0.11 | 0.07 | 0.07 | 0.13 | 0.13 | 0.17 | 0.10 | 0.04 |
| | SMOG | 0.29 | 0.07 | 0.25 | 0.07 | 0.40 | 0.35 | 0.35 | 0.17 | 0.24 | 0.12 |
| | ACID | 0.10 | 0.19 | 0.08 | 0.07 | 0.10 | 0.08 | 0.08 | 0.17 | 0.11 | 0.04 |
| | HHCR | 0.29 | 0.55 | 0.03 | 0.07 | 0.01 | 0.35 | 0.35 | 0.17 | 0.23 | 0.18 |
| | Energy Consumption | 0.10 | 0.12 | 0.01 | 0.35 | 0.12 | 0.08 | 0.08 | 0.17 | 0.13 | 0.09 |
| Subcriteria/ Social | Social Costs | 0.50 | 0.26 | 0.37 | 0.18 | 0.18 | 0.50 | 0.82 | 0.50 | 0.41 | 0.20 |
| | Social Emissions | 0.50 | 0.74 | 0.08 | 0.82 | 0.82 | 0.50 | 0.18 | 0.50 | 0.52 | 0.26 |

**Table 3.15 Calculated Final Weightages for Designs based on the Inputs from Decision Makers (Traditional AHP)**

| Design | Decision Maker(DM) weightages | | | | | | | | Average | Standard Deviation |
|---|---|---|---|---|---|---|---|---|---|---|
| | DM1 | DM2 | DM3 | DM4 | DM5 | DM6 | DM7 | DM8 | | |
| Design 1 | 0.17 | 0.34 | 0.40 | 0.13 | 0.10 | 0.22 | 0.15 | 0.32 | 0.22 | 0.11 |
| Deisgn 2 | 0.23 | 0.27 | 0.30 | 0.21 | 0.32 | 0.19 | 0.18 | 0.23 | 0.24 | 0.05 |
| Design 3 | 0.25 | 0.19 | 0.15 | 0.25 | 0.20 | 0.27 | 0.33 | 0.24 | 0.23 | 0.05 |
| Design 4 | 0.36 | 0.14 | 0.15 | 0.41 | 0.38 | 0.32 | 0.34 | 0.36 | 0.30 | 0.10 |

**Table 3.16 Calculated Final Weightages for Designs based on the Inputs from Decision Makers (Proposed AHP)**

| Design | Decision Maker(DM) weightages | | | | | | | | Average | Standard Deviation |
|---|---|---|---|---|---|---|---|---|---|---|
| | DM1 | DM2 | DM3 | DM4 | DM5 | DM6 | DM7 | DM8 | | |
| Design 1 | 0.19 | 0.32 | 0.43 | 0.16 | 0.14 | 0.22 | 0.20 | 0.26 | 0.24 | 0.09 |
| Design 2 | 0.23 | 0.30 | 0.28 | 0.22 | 0.26 | 0.20 | 0.13 | 0.22 | 0.23 | 0.05 |
| Design 3 | 0.26 | 0.22 | 0.11 | 0.26 | 0.18 | 0.28 | 0.39 | 0.22 | 0.24 | 0.08 |
| Design 4 | 0.32 | 0.16 | 0.17 | 0.36 | 0.42 | 0.30 | 0.29 | 0.31 | 0.29 | 0.08 |

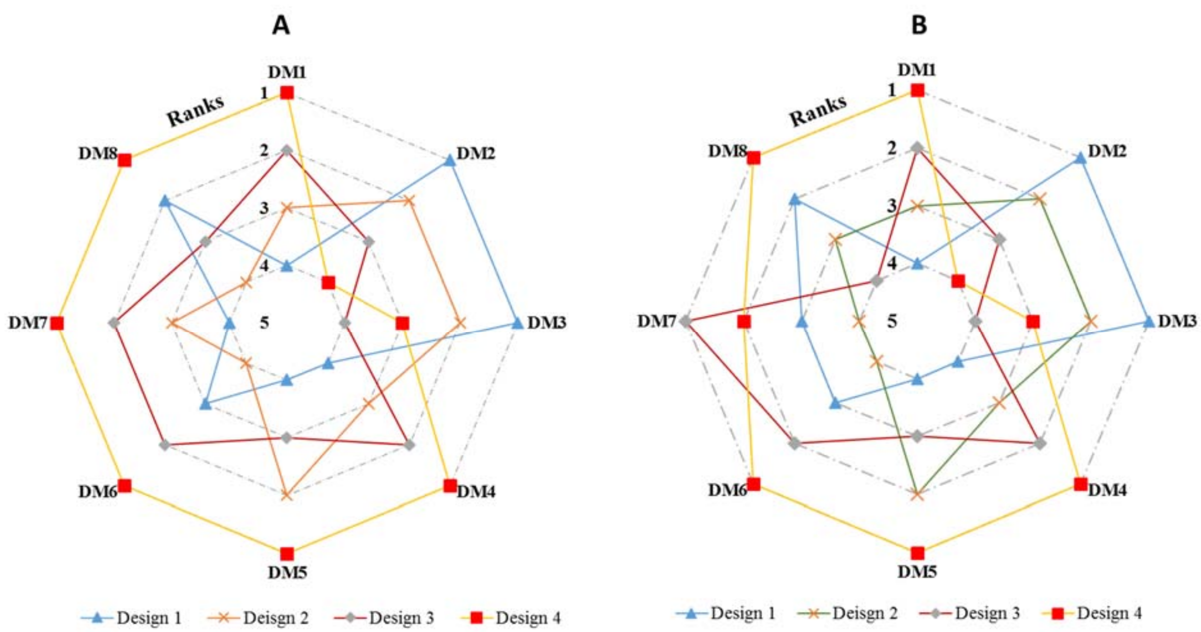


**Figure 3.13 Ranking of Four Designs by Eight Experts A) Traditional AHP, B) Proposed AHP**

To resolve above mentioned issues, a new group decision model was proposed in this dissertation. This study introduced a group decision model by using the Data Envelopment Analysis (DEA) based preference aggregation method to combine the individual inputs into group decision in conjunction with α constrained particle swarm optimization technique to generate consistent results in minimal time without altering individual decision maker inputs. The complete details about the concepts of proposed method were explained in Appendix I.

### 3.5.2. Group Decision Model

The cross functional flow chart of various concepts involved in the group decision model is illustrated in Figure 3.14. The proposed method is exemplified through calculation of group weights for data in Table 3.17. The steps followed are given below:

Step 1: Convert the weightages in
Table 3.17 into a rank matrix R as shown below.

| Design | DM1 | DM2 | DM3 | DM4 | DM5 | DM6 | DM7 | DM8 |
|---|---|---|---|---|---|---|---|---|
| Design1 | 4 | 1 | 1 | 4 | 4 | 3 | 3 | 2 |
| Design2 | 3 | 2 | 2 | 3 | 2 | 4 | 4 | 3 |
| Design3 | 2 | 3 | 4 | 2 | 3 | 2 | 1 | 4 |
| Design4 | 1 | 4 | 3 | 1 | 1 | 1 | 2 | 1 |

Step 2: Develop matrix S from R which indicates number of times each design is placed in a particular rank.

| Design | Rank1 | Rank2 | Rank3 | Rank4 |
|---|---|---|---|---|
| Design1 | 2 | 1 | 2 | 3 |
| Design2 | 0 | 3 | 3 | 2 |
| Design3 | 1 | 3 | 2 | 2 |
| Design4 | 5 | 1 | 1 | 1 |

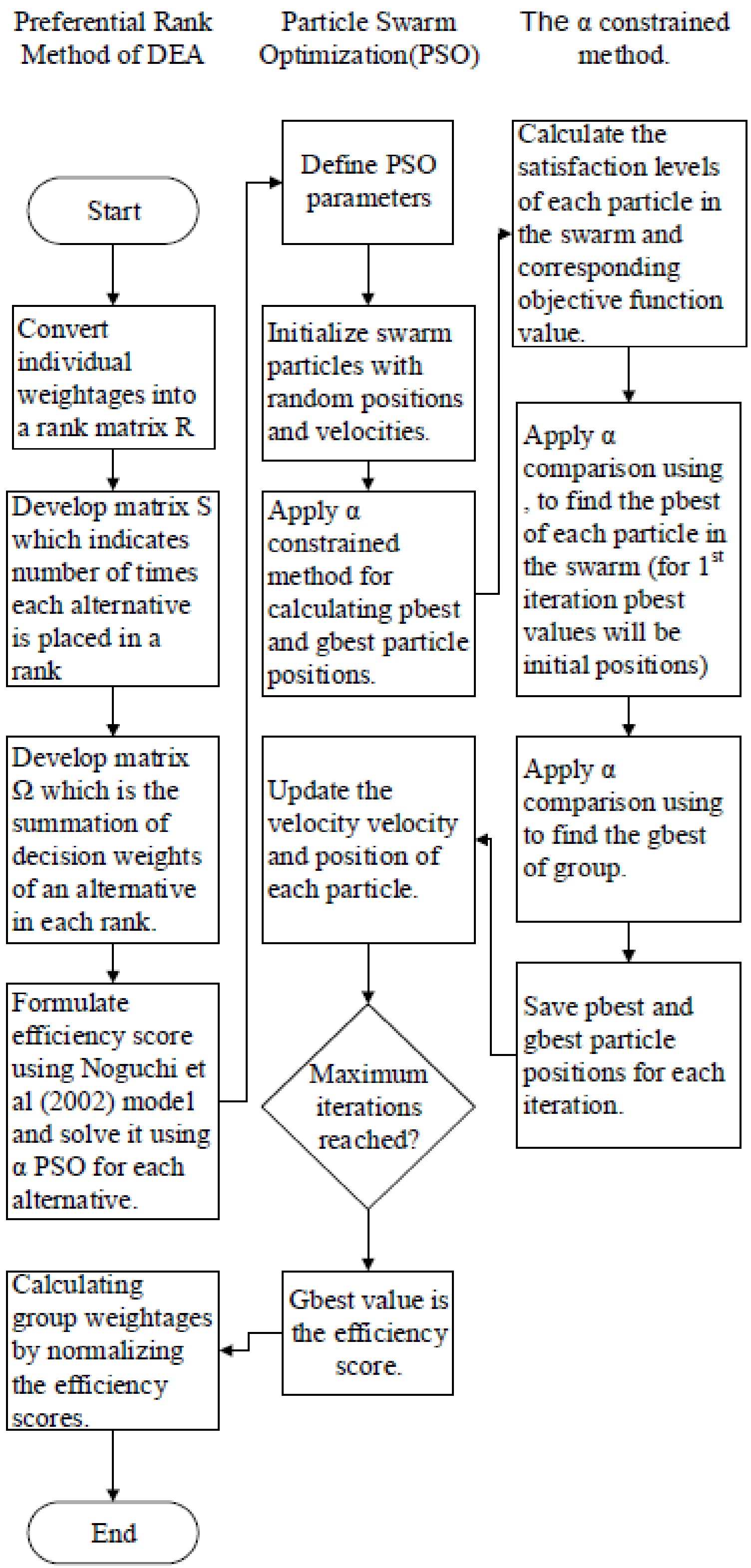


**Figure 3.14 Cross Functional Flowchart of Preferential Rank Method of Data Envelopment Analysis, Particle Swarm Optimization and α Constrained Method**

**Table 3.17 Final Weightages Obtained from Eight Decision Makers (Proposed AHP)**

| Design | Decision Maker(DM) weightages | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **DM1** | **DM2** | **DM3** | **DM4** | **DM5** | **DM6** | **DM7** | **DM8** |
| Design 1 | 0.190 | 0.320 | 0.434 | 0.160 | 0.139 | 0.221 | 0.196 | 0.257 |
| Design 2 | 0.226 | 0.301 | 0.280 | 0.224 | 0.259 | 0.196 | 0.128 | 0.215 |
| Design 3 | 0.264 | 0.218 | 0.112 | 0.256 | 0.180 | 0.283 | 0.391 | 0.215 |
| Design 4 | 0.320 | 0.160 | 0.174 | 0.360 | 0.422 | 0.300 | 0.285 | 0.312 |

Step 3: Develop matrix Ω which is the summation of decision weights of each design in each rank.

$$\begin{bmatrix} \text{Design} & \text{Rank1} & \text{Rank2} & \text{Rank3} & \text{Rank4} \\ \text{Design1} & 0.754 & 0.257 & 0.417 & 0.489 \\ \text{Design2} & 0.000 & 0.840 & 0.665 & 0.324 \\ \text{Design3} & 0.391 & 0.803 & 0.613 & 0.112 \\ \text{Design4} & 1.714 & 0.285 & 0.174 & 0.160 \end{bmatrix}$$

Step 4: Calculate efficiency score for each design.

The DEA model proposed by Noguchi et al. (2002) is used to find the efficiency score. As per the model, the efficiency score for Design1 was achieved by maximizing the following equation:

$$\begin{cases} eff_{design1} \ \max 0.754u_1 + 0.257u_2 + 0.417u_3 + 0.489u_4 \\ \quad \textit{Subjected to} \\ 0.754u_1 + 0.257u_2 + 0.417u_3 + 0.489u_4 \leq 1 \\ 0.000u_1 + 0.840u_2 + 0.665u_3 + 0.324u_4 \leq 1 \\ 0.391u_1 + 0.803u_2 + 0.613u_3 + 0.112u_4 \leq 1 \\ 1.714u_1 + 0.285u_2 + 0.174u_3 + 0.160u_4 \leq 1 \\ u_1 \geq 2u_2 \geq 3u_3 \geq 4u_4 \\ u_4 \geq \mathcal{E} = \frac{2}{pn(n+1)} = \frac{2}{8\times4\times(5)} = 0.0125 \end{cases} \quad \textbf{3.2}$$

Similarly, the efficiency score for quality, safety and experience can be calculated by solving the following equations 3, 4 & 5, with the constraints similar to equation 3.2

$$eff_{design2} \ \max 0.000u_1 + 0.840u_2 + 0.665u_3 + 0.324u_4 \quad \textbf{3.3}$$

$$eff_{design3} \quad max\ 0.391u_1 + 0.803u_2 + 0.613u_3 + 0.112u_4 \qquad \textbf{3.4}$$

$$eff_{design4} \quad \max 1.714u_1 + 0.285u_2 + 0.174u_3 + 0.160u_4 \qquad \textbf{3.5}$$

For solving the above linear programming equations, a hybrid approach was proposed in this study which combines α-PSO with a partial feasible solution. The details of the proposed method were given in Appendix I.

To evaluate the valuableness of the proposed optimization method, the above equations were solved using a commercially available optimization software TORA. The comparison of both the results are given in the following Table 3.18. It is evident from the results that both methods yielded similar efficiency scores.

**Table 3.18 Efficiency Scores for Designs Calculated using TORA and Proposed Optimization Method**

| Design | Efficiency Scores | |
|---|---|---|
| | TORA | Proposed Optimization Method |
| Design 1 | 0.510 | 0.510 |
| Design 2 | 0.210 | 0.213 |
| Design 3 | 0.400 | 0.382 |
| Design 4 | 1.000 | 1.000 |

Step 5:

Calculate the group weights by normalizing efficiency scores. The Table 3.19 shows the final weights for the four designs. It is apparent that Design 4 achieved maximum weightage in all methods. However, the proposed group decision model in conjunction with suggested optimization method yielded relatively higher weight for Design 4 compared to just averaging. The proposed methods clearly distinguish each design ranking and assists in making the final decision. By following the same procedure, the group weights were calculated for all criterion, and sub-criterion and Table 3.20 shows the group weights.

Figure 3.15 displays the final group weights achieved by the four designs using proposed AHP and traditional AHP. It is apparent from this case study that Design 4 is the most preferred design based on sustainable criteria.

**Table 3.19 Final Weightages Assigned to Four Designs**

| Design | Group Weightages | | |
|---|---|---|---|
| | Average | TORA | Proposed Optimization Method |
| Design 1 | 0.24 | 0.24 | 0.24 |
| Design 2 | 0.23 | 0.10 | 0.10 |
| Design 3 | 0.24 | 0.19 | 0.18 |
| Design 4 | 0.29 | 0.47 | 0.48 |

**Table 3.20 Group Weightages Criteria/Sub-criteria**

| Comparing | Criteria/ sub-criteria | Group Weightages | | | | | |
|---|---|---|---|---|---|---|---|
| | | Traditional AHP | | | Proposed AHP | | |
| | | Average | TORA | α PSO | Average | TORA | α PSO |
| Main Criteria | Economy | 0.36 | 0.37 | 0.38 | 0.40 | 0.45 | 0.45 |
| | Environment | 0.35 | 0.37 | 0.37 | 0.32 | 0.27 | 0.28 |
| | Social | 0.29 | 0.25 | 0.25 | 0.28 | 0.28 | 0.28 |
| Subcriteria/ Economy | Agency Costs | 0.45 | 0.44 | 0.44 | 0.45 | 0.44 | 0.44 |
| | User Costs | 0.55 | 0.56 | 0.56 | 0.55 | 0.56 | 0.56 |
| Subcriteria/ Environment | GWP | 0.20 | 0.23 | 0.24 | 0.19 | 0.20 | 0.21 |
| | EUT | 0.09 | 0.05 | 0.06 | 0.10 | 0.06 | 0.05 |
| | SMOG | 0.20 | 0.20 | 0.18 | 0.24 | 0.29 | 0.28 |
| | ACID | 0.13 | 0.06 | 0.07 | 0.11 | 0.04 | 0.05 |
| | HHCR | 0.21 | 0.31 | 0.31 | 0.23 | 0.30 | 0.29 |
| | Energy Consumption | 0.16 | 0.14 | 0.14 | 0.13 | 0.11 | 0.11 |
| Subcriteria/ Social | Social Costs | 0.47 | 0.46 | 0.46 | 0.41 | 0.46 | 0.46 |
| | Social Emissions | 0.53 | 0.54 | 0.54 | 0.52 | 0.54 | 0.54 |

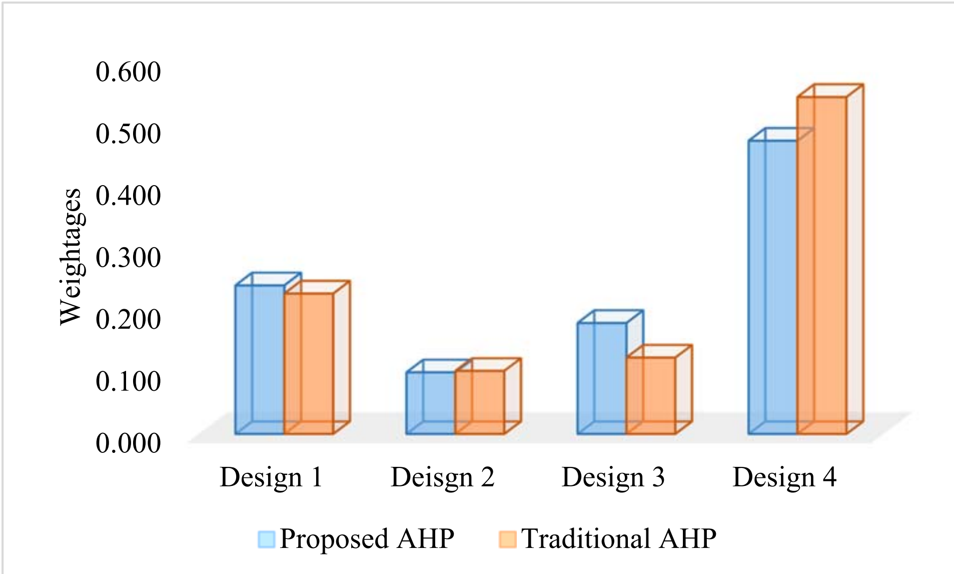


**Figure 3.15 Group Weightages Assigned to Four Designs**

# Chapter 4. Closure

The depletion of natural resources, the decrease in financial resources, and increased public awareness of the environment have shifted the focus of highway engineers and planners to design and construct sustainable pavements. However, the sustainability principles in entirety have not been implemented. In other words, researchers and practitioners used recycled materials to satisfy sustainability without accounting for the additional energy required in producing recycled materials. Therefore, a comprehensive approach for selection of sustainable pavement design was proposed and evaluated in this study by integrating LCCA (economic), LCA-E (environmental), and LCA-S (social) criteria that satisfy three pillars of sustainability.

Life cycle assessment (LCCA, LCA-E, and LCA-S) methods were chosen in this study because they evaluate the impacts throughout the life cycle of pavements rather than at the time of construction. Moreover, they expose possible future hazards in a particular phase of the project and help to mitigate them. For example, the significance of traffic delay emissions during maintenance operations was evaluated on to how it can overwhelm the emissions from other phases if maintenance occurs from 9 AM-5 PM.

Each life cycle assessment method considered in the study is at a different level of advancement. By performing all of the evaluations, the intertwined relationships between them and their complementary nature was identified. For instance, a detailed cost estimate during LCCA was helpful while performing LCA-E. Similarly, the user costs estimation method in LCCA supported emissions estimation during maintenance operations due to traffic delays.

The databases and assessments models (RealCost2.5, GREET, NONROAD, RSMeans, TNM2.5, MOVES, etc.) were selected because these models are available to practitioners, and most of the databases were exclusively developed by federal agencies like the US EPA, FHWA, etc. In this study, common inputs (future traffic growth, vehicle classification, project logistics, etc.) required for three methods were assumed to be the same since each assessment method requires similar inputs for predicting future impacts.

For this study, a multi-criteria group decision model was also developed. The proposed decision models were developed using simple analytic yet efficient processes such as fuzzy methods, artificial intelligence techniques, etc. The decision model can accommodate subjective as well as objective data sets, reduces the efforts required from decision-makers, and strives towards achieving maximum satisfaction from decision-makers (group decision).

This framework will assist planning and design engineers as it allows them to foresee the risks or benefits of their decisions. This study also demonstrated the amount of effort and level of details required to assess the sustainability parameters.

In the end, a case study was fabricated to perform sustainability evaluation. Four alternate pavement structure designs were developed and evaluated by including three pillars of sustainability. Based on input provided by the expert panel, Design 4 was ranked as the most preferred sustainable design. Although rated higher, it does not imply that Design 4 is a sustainable design in all projects. The concept of sustainability is case sensitive, and there will be numerous factors that influence the design selection in every project.

Even though the proposed method is demonstrated for sustainability evaluation of pavement structure design, it can be easily adapted to other sustainable infrastructure decisions. The primary purpose of performing a case study is to exhibit the computations involved in sustainability rather than to endorse any particular design. The importance of the proposed framework will be more valuable if applied to a real highway project.

This study significantly contributes towards sustainable infrastructure, more specifically to highways, and the key contributions from this dissertation are:

- Proposed a framework for selecting pavement design by integrating the three pillars of sustainability.
- Proposed a new methodology for performing normalization and weighting methods in LCIA of LCA-E.
- Proposed a new methodology for estimating emissions due to traffic delays during scheduled maintenance.

- Proposed a framework for performing LCA-S of pavements.
- Proposed ‘traffic noise ‘as a feasible social impact indicator and demonstrated the impact of traffic noise on sustainability.
- Proposed a group decision model by integrating Data Envelopment Analysis (DEA), Particle Swarm Optimization (PSO), and the Analytic Hierarchy Process (AHP).
- Proposed a hybrid Particle swarm optimization method to handle multiple constraints and find a solution in less computational time.
- Proposed a methodology to enhance the AHP by reducing the number of pairwise comparisons to maintain the consistency requirements of AHP.

## 4.1. Limitations and Future Research

The focus of this study was to demonstrate how economic, environmental, and social parameters of sustainability can be integrated into pavement design selection. The indicators (GWP, user-costs, traffic noise, etc.) used in this study were not a complete indicator set; instead, they were only a limited number of feasible indicators. Future users can incorporate other feasible indicators into this framework.

In LCCA’s probabilistic approach, some input probability distribution functions and values were assumed just to explain the methodology. Future study is required to establish the probability distribution functions of various inputs in LCCA based on real project data.

In LCA-E, only air pollutants and six impact categories were assessed. The inclusion of other impact categories and water-born pollutants can be performed to identify their impact on sustainability in the future. The “use phase” in LCA-E is ignored due to lack of performance prediction models for different pavement types, but “use phase” is a significant one and needs to be included in future studies.

Future study is also required to identify possible social impact indicators, other than traffic noise, that help in distinguishing various pavement designs.

In the group decision model, decisions from all decision-makers were considered equally important. Two drawbacks were identified while performing the decision analysis.

1. Confidence levels of each decision-maker varied based on their expertise. For example, a decision-maker who has experience in construction is more confident in understanding economic impacts compared with environmental. His/her decisions towards the environment are solely based on the numerical values rather than understanding the impacts. So, the decision model needs to be further modified to include the confidence levels of each decision-maker towards their choices.
2. The decision group was comprised of people with different years of experience (2< experience<35 years). Assigning equal importance to every decision maker's choices may not be logical, and hence the decision model needs to include the experience factor.

Further study is required to analyze other multi-criteria decision-making models, and to employ them in sustainable decision-making. More specific limitations and future research recommendations were presented in each manuscript kept in Appendices.

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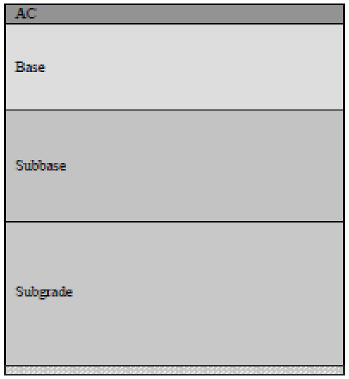
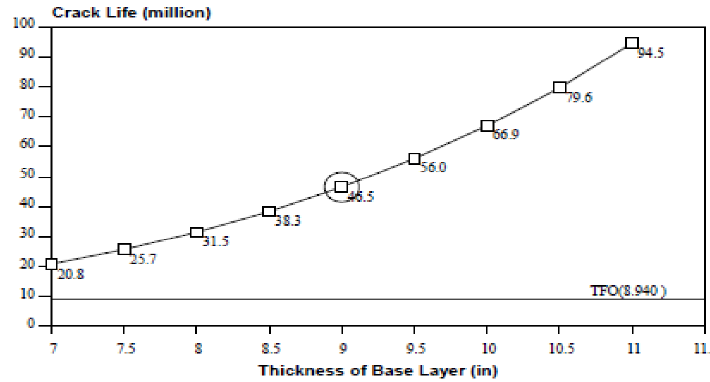
# Appendix A

## (Performance analysis of four designs)




| Thickness (inches) | Modulus (ksi) | Poisson's Ratio | Material Name |
|---|---|---|---|
| 2.00 | 500.00 | 0.35 | ASPH CONC PVMT |
| 9.00 | 400.00 | 0.35 | ASPH STAB BASE |
| 11.50 | 48.00 | 0.33 | FLEXIBLE BASE |
| 200.00 | 16.00 | 0.40 | SUBGRADE(200) |




*Fatigue Crack Model:*

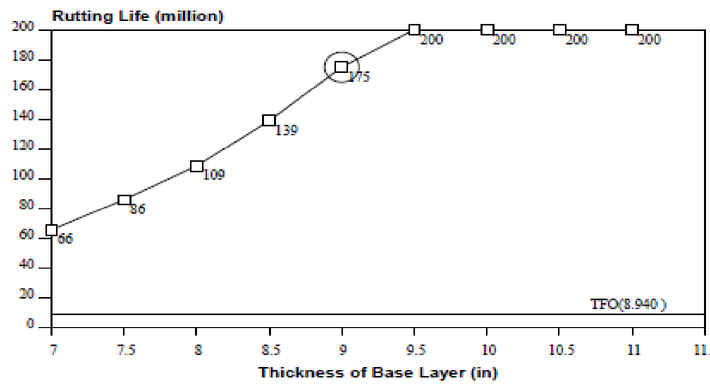
$$N_f = f_1 (\varepsilon_t)^{-f_2} (E_1)^{-f_3}$$

$f_1$ =7.96E-02
$f_2$ = 3.291
$f_3$ = .854

*Rutting Model:*

$$N_d = f_4 (\varepsilon_v)^{-f_5}$$

$f_4$ =1.37E-09
$f_5$ = 4.477




TFO(Traffic to 1st Overlay): 8.94 (million)

Crack Life: 46.49 (million) $\varepsilon_t$ = 76.30 ( με )

Rut Life: 175.16 (million) $\varepsilon_v$ = -151.00 ( με )

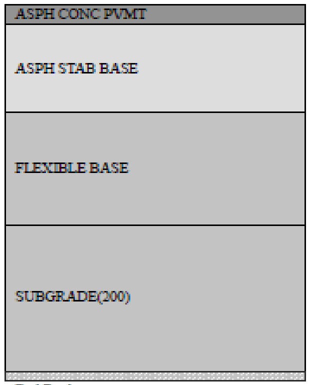
Traffic to 1st Overlay is calculated by analysis period: 30years and 18 kips:22.81millions.
Also the start ADT:61236.0 and ending ADT:75102.0

*Mechanistic Check Conclusion:*

The design is OK !

| FPS 21 Mechanistic Design Check Output (FPS21-1.3Release:12-7-2012) | | | |
|---|---|---|---|
| Highway | IH10 | Problem | 006 |
| C-S-J | 1234 - 2 - 123 | Date | 10/27/2014 |
| District | El Paso | County | EL PASO |
| *Design Type:Asphalt concrete + Asphalt Stabilized Base + Flexible Base over Subgrade* | | | |

**Figure A.1 Mechanistic Check (Rutting and Fatigue) for Design 1.**




| Layer | Thickness (inches) | Modulus (ksi) | Poisson's Ratio | Material Name |
|---|---|---|---|---|
| ASPH CONC PVMT | 2.00 | 500.00 | 0.35 | ASPH CONC PVMT |
| ASPH STAB BASE | 9.00 | 400.00 | 0.35 | ASPH STAB BASE |
| FLEXIBLE BASE | 11.50 | 48.00 | 0.33 | FLEXIBLE BASE |
| SUBGRADE(200) | 200.00 | 16.00 | 0.40 | SUBGRADE(200) |
| Bed Rock | | 1600.00 | 0.15 | Bed Rock |

**INPUT PARAMETERS:**

| | |
|---|---|
| The Heaviest Wheel Loads Daily (ATHWLD) | 13800.0 (lb) |
| Percentage of TandemAxles | 60.0 (%) |
| Modified Cohesionmeter Value | 100.0 |
| Design Wheel Load | 17940.0 (lb) |
| Subgrade Texas Triaxial Class Number (TTC) | 3.40 |

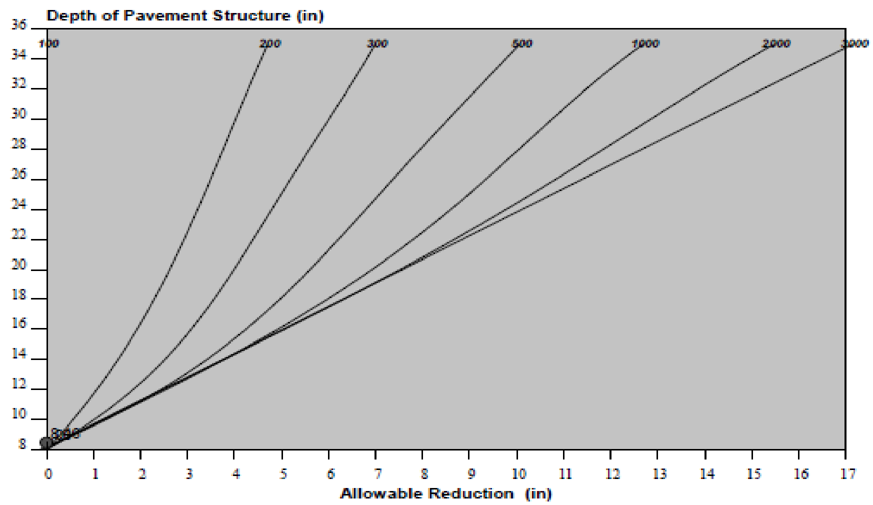
TTC is based on Texas County Soil Database for (EL PASO)
For soils type : silty sand(SM) + clayey sand(SC)

**RESULT:**

| | |
|---|---|
| Triaxial Thickness Required | 8.5 (in) |
| The FPS Design Thickness | 22.5 (in) |
| Allowable Thickness Reduction | 0.0 (in) |
| Modified Triaxial Thickness | 8.5 (in) |

**TRIAXIAL CHECK CONCLUSION:**

The Design OK !

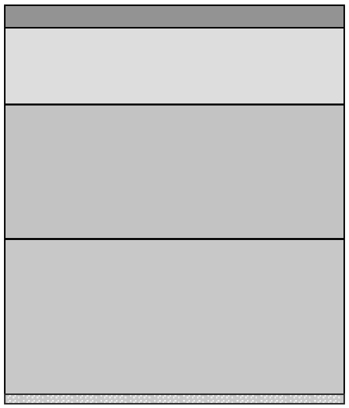



Thickness Reduction Chart for Stabilized Layers

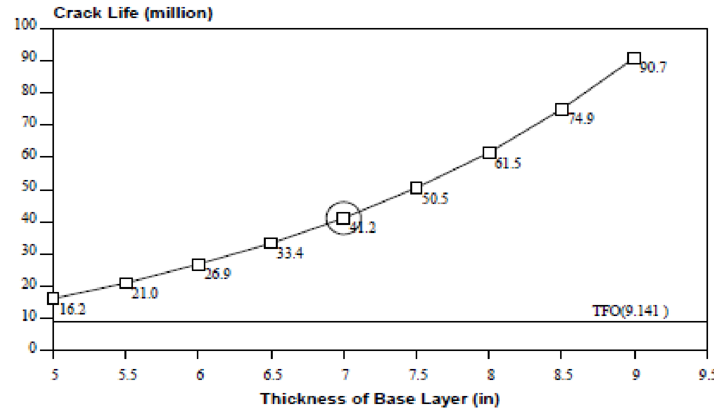
| FPS 21 Triaxial Design Check Output (FPS21-1.3Release:12-7-2012) | | | |
|---|---|---|---|
| Highway | IH10 | Problem | 006 |
| C-S-J | 1234 - 2 - 123 | Date | 10/27/2014 |
| District | El Paso | County | EL PASO |

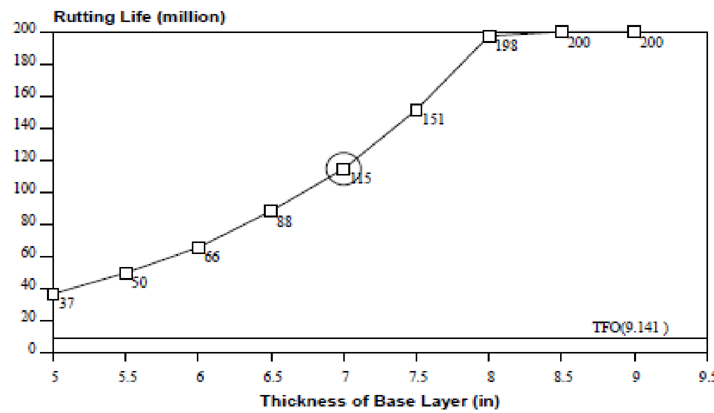
*Design Type:Asphalt concrete + Asphalt Stabilized Base + Flexible Base over Subgrade*

**Figure A.2 Triaxial Check for Design 1**



| Thickness (inches) | Modulus (ksi) | Poisson's Ratio | Material Name |
|---|---|---|---|
| 2.00 | 300.00 | 0.30 | PFC |
| 7.00 | 650.00 | 0.35 | DENSE-GRADED HMA Thick |
| 12.00 | 70.00 | 0.30 | LIME STABILIZED BASE |
| 200.00 | 16.00 | 0.40 | SUBGRADE |




***Fatigue Crack Model:***

$$N_f = f_1 (\varepsilon_t)^{-f_2} (E_1)^{-f_3}$$

$f_1$ =7.96E-02

$f_2$ = 3.291

$f_3$ = .854

***Rutting Model:***

$$N_d = f_4 (\varepsilon_v)^{-f_5}$$

$f_4$ =1.37E-09

$f_5$ = 4.477

TFO(Traffic to 1st Overlay): 9.14 (million)

Crack Life: 41.17 (million) $\varepsilon_t$ = 69.80 ( $\mu\varepsilon$ )

Rut Life: 114.63 (million) $\varepsilon_v$ = -166.00 ( $\mu\varepsilon$ )

Traffic to 1st Overlay is calculated by analysis period: 30years and 18 kips:22.81millions.
Also the start ADT:61236.0 and ending ADT:75102.0

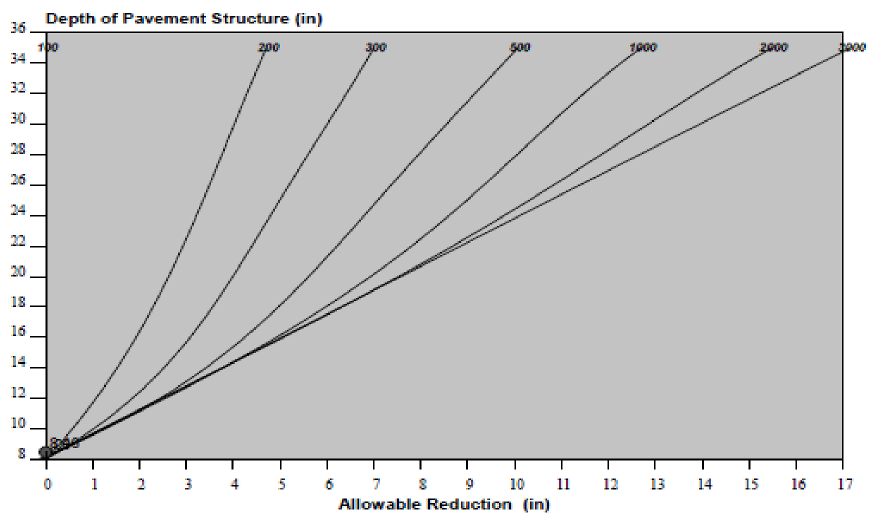
***Mechanistic Check Conclusion:***

The design is OK !

| FPS 21 Mechanistic Design Check Output (FPS21-1.3Release:12-7-2012) | | | |
|---|---|---|---|
| Highway | IH10 | Problem | 006 |
| C-S-J | 1234 - 2 - 123 | Date | 10/28/2014 |
| District | El Paso | County | EL PASO |
| *Design Type:User Defined Pavement Design* | | | |

**Figure A.3 Mechanistic Check (Rutting and Fatigue) for Design 2**

| Layer | Thickness (inches) | Modulus (ksi) | Poisson's Ratio | Material Name |
|---|---|---|---|---|
| PFC | 2.00 | 300.00 | 0.30 | PFC |
| DENSE-GRADED HMA Thick | 7.00 | 650.00 | 0.35 | DENSE-GRADED HMA Thick |
| LIME STABILIZED BASE | 12.00 | 70.00 | 0.30 | LIME STABILIZED BASE |
| SUBGRADE | 200.00 | 16.00 | 0.40 | SUBGRADE |
| Bed Rock | | 1600.00 | 0.15 | Bed Rock |




Thickness Reduction Chart for Stabilized Layers

**INPUT PARAMETERS:**

| | |
|---|---|
| The Heaviest Wheel Loads Daily (ATHWLD) | 13800.0 (lb) |
| Percentage of TandemAxles | 60.0 (%) |
| Modified Cohesionmeter Value | 100.0 |
| Design Wheel Load | 17940.0 (lb) |
| Subgrade Texas Triaxial Class Number (TTC) | 3.40 |

TTC is based on Texas County Soil Database for (EL PASO)

For soils type : silty sand(SM) + clayey sand(SC)

**RESULT:**

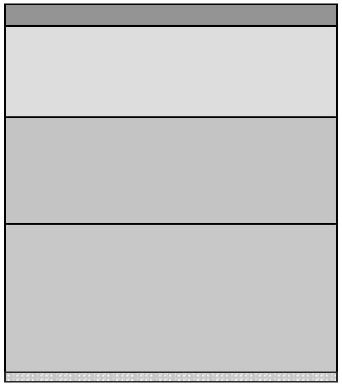
| | |
|---|---|
| Triaxial Thickness Required | 8.5 (in) |
| The FPS Design Thickness | 21.0 (in) |
| Allowable Thickness Reduction | 0.0 (in) |
| Modified Triaxial Thickness | 8.5 (in) |

**TRIAXIAL CHECK CONCLUSION:**

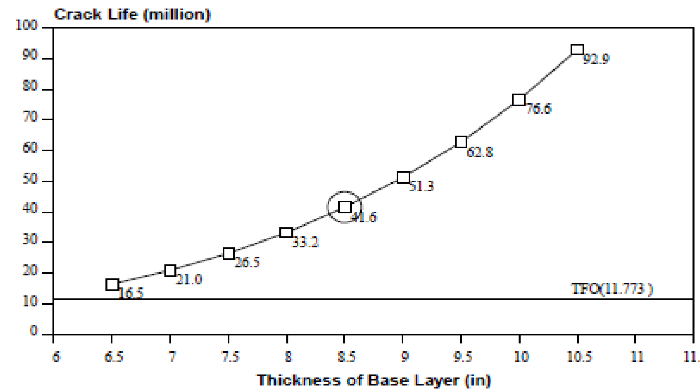
The Design OK !

| FPS 21 Triaxial Design Check Output | (FPS21-1.3Release:12-7-2012) | | |
|---|---|---|---|
| Highway | IH10 | Problem | 006 |
| C-S-J | 1234 - 2 - 123 | Date | 10/28/2014 |
| District | El Paso | County | EL PASO |
| *Design Type:User Defined Pavement Design* | | | |

**Figure A.4 Triaxial Check for Design 2**



| Thickness (inches) | Modulus (ksi) | Poisson's Ratio | Material Name |
|---|---|---|---|
| 2.00 | 500.00 | 0.35 | DENSE-GRADED HMA Thin |
| 8.50 | 650.00 | 0.35 | DENSE-GRADED HMA Thick |
| 10.00 | 35.00 | 0.30 | FA OR LIME-FLY ASH STAB |
| 200.00 | 16.00 | 0.40 | SUBGRADE |




***Fatigue Crack Model:***

$$N_f = f_1 (\varepsilon_t)^{-f_2} (E_1)^{-f_3}$$

$f_1$ =7.96E-02

$f_2$ =3.291

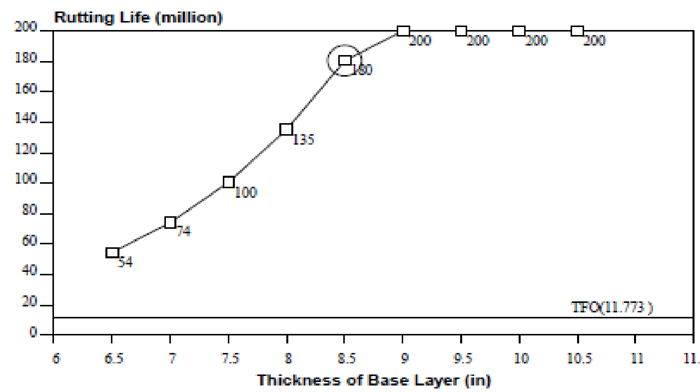
$f_3$ =.854

***Rutting Model:***

$$N_d = f_4 (\varepsilon_v)^{-f_5}$$

$f_4$ =1.37E-09

$f_5$ =4.477




TFO(Traffic to 1st Overlay): 11.77 (million)

Crack Life: 41.56 (million) $\varepsilon_t$ = 69.60 ( με )

Rut Life: 180.45 (million) $\varepsilon_v$ = -150.00 ( με )

Traffic to 1st Overlay is calculated by analysis period: 30years and 18 kips:22.81millions.
Also the start ADT:61236.0 and ending ADT:75102.0

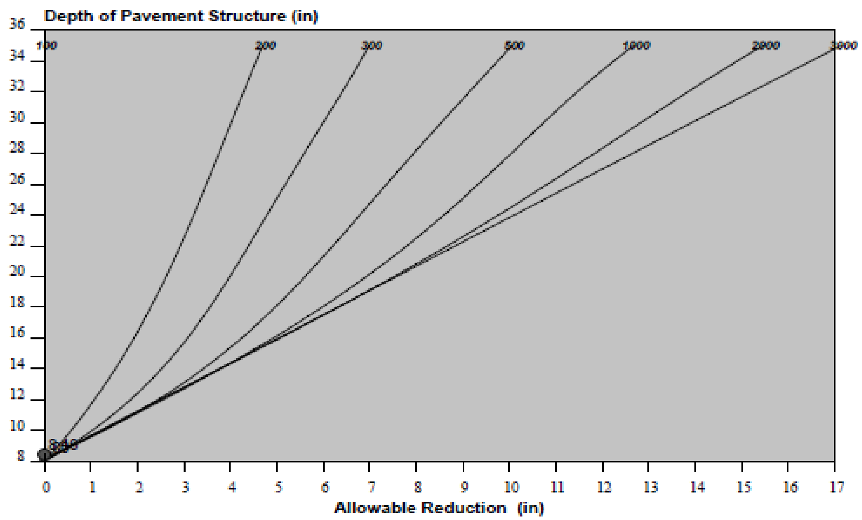
***Mechanistic Check Conclusion:***

The design is OK !

| FPS 21 Mechanistic Design Check Output | (FPS21-1.3Release:12-7-2012) | | |
|---|---|---|---|
| Highway | IH10 | Problem | 006 |
| C-S-J | 1234 - 2 - 123 | Date | 10/28/2014 |
| District | El Paso | County | EL PASO |
| *Design Type:User Defined Pavement Design* | | | |

**Figure A.5 Mechanistic Check (Rutting and Fatigue) for Design 3**

| | Thickness (inches) | Modulus (ksi) | Poisson's Ratio | Material Name |
|---|---|---|---|---|
| DENSE-GRADED HMA Thin | 2.00 | 500.00 | 0.35 | DENSE-GRADED HMA Thin |
| DENSE-GRADED HMA Thick | 9.00 | 650.00 | 0.35 | DENSE-GRADED HMA Thick |
| FA OR LIME-FLY ASH STAB | 6.00 | 35.00 | 0.30 | FA OR LIME-FLY ASH STAB |
| SUBGRADE | 200.00 | 16.00 | 0.40 | SUBGRADE |
| Bed Rock | | 1600.00 | 0.15 | Bed Rock |




Thickness Reduction Chart for Stabilized Layers

**INPUT PARAMETERS:**

| | |
|---|---|
| The Heaviest Wheel Loads Daily (ATHWLD) | 13800.0 (lb) |
| Percentage of TandemAxles | 60.0 (%) |
| Modified Cohesionmeter Value | 100.0 |
| Design Wheel Load | 17940.0 (lb) |
| Subgrade Texas Triaxial Class Number (TTC) | 3.40 |

TTC is based on Texas County Soil Database for (EL PASO)

For soils type : silty sand(SM) + clayey sand(SC)

**RESULT:**

| | |
|---|---|
| Triaxial Thickness Required | 8.5 (in) |
| The FPS Design Thickness | 17.0 (in) |
| Allowable Thickness Reduction | 0.0 (in) |
| Modified Triaxial Thickness | 8.5 (in) |

**TRIAXIAL CHECK CONCLUSION:**

The Design OK !

| FPS 21 Triaxial Design Check Output | (FPS21-1.3Release:12-7-2012) | | |
|---|---|---|---|
| Highway | IH10 | Problem | 008 |
| C-S-J | 1234 - 2 - 123 | Date | 10/28/2014 |
| District | El Paso | County | EL PASO |

*Design Type:User Defined Pavement Design*

**Figure A.6 Triaxial Check for Design 3**

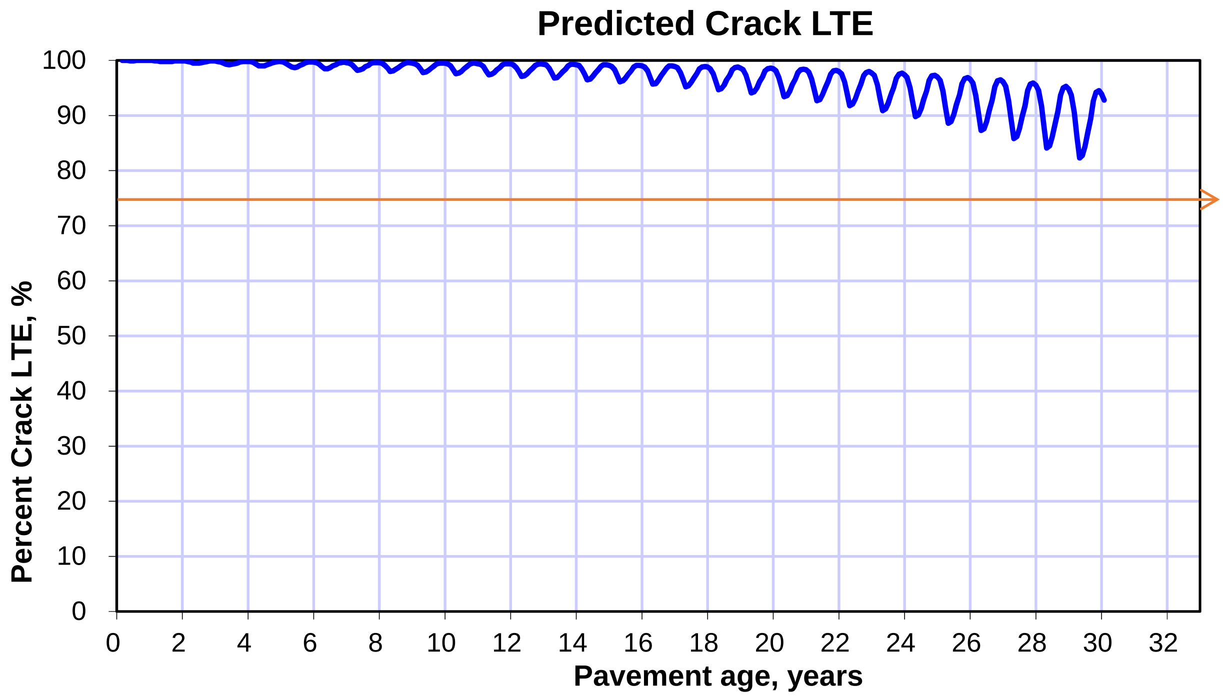



**Figure A.7 Predicted Load Transfer Efficiency (LTE) of Design 4**

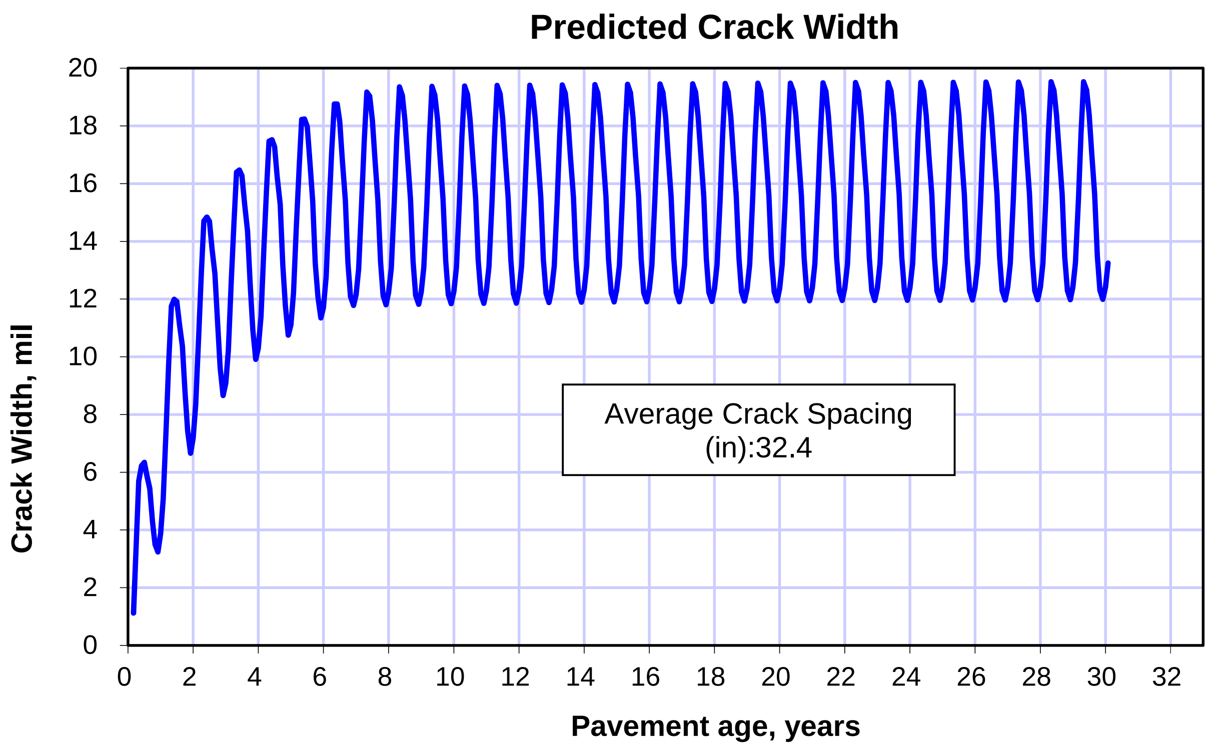



**Figure A.8 Predicted Crack Width of Design 4**

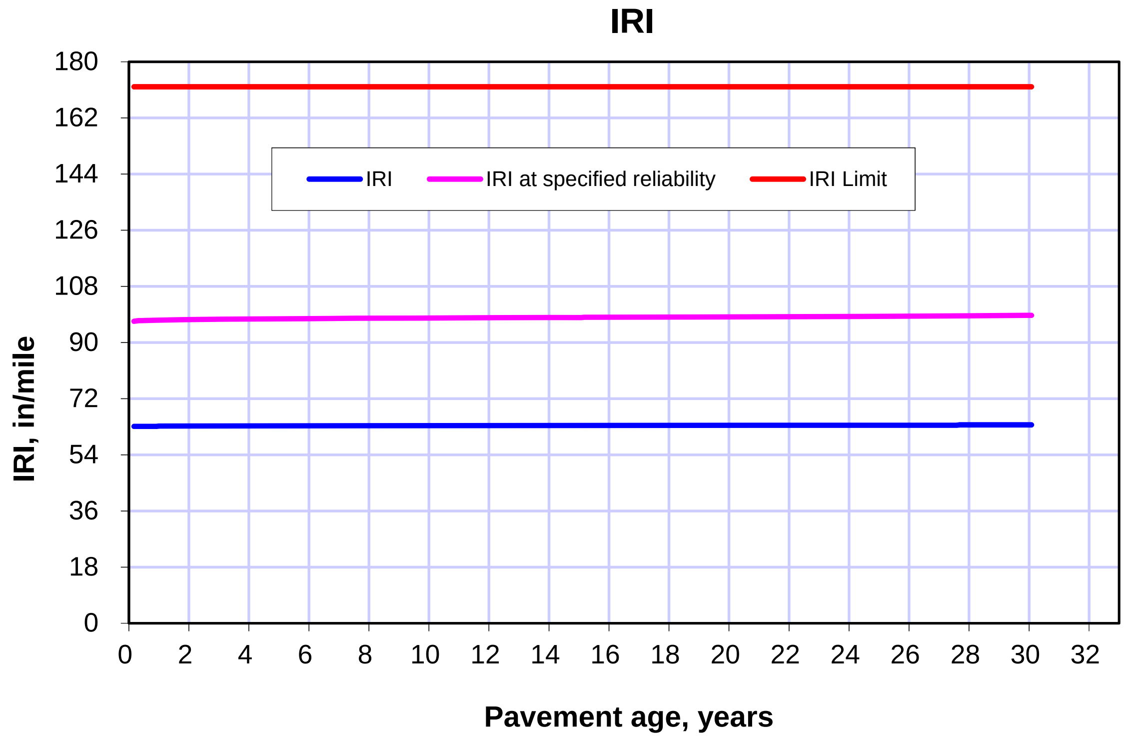



**Figure A.9 Predicted International Roughness Index (IRI) of Design 4**

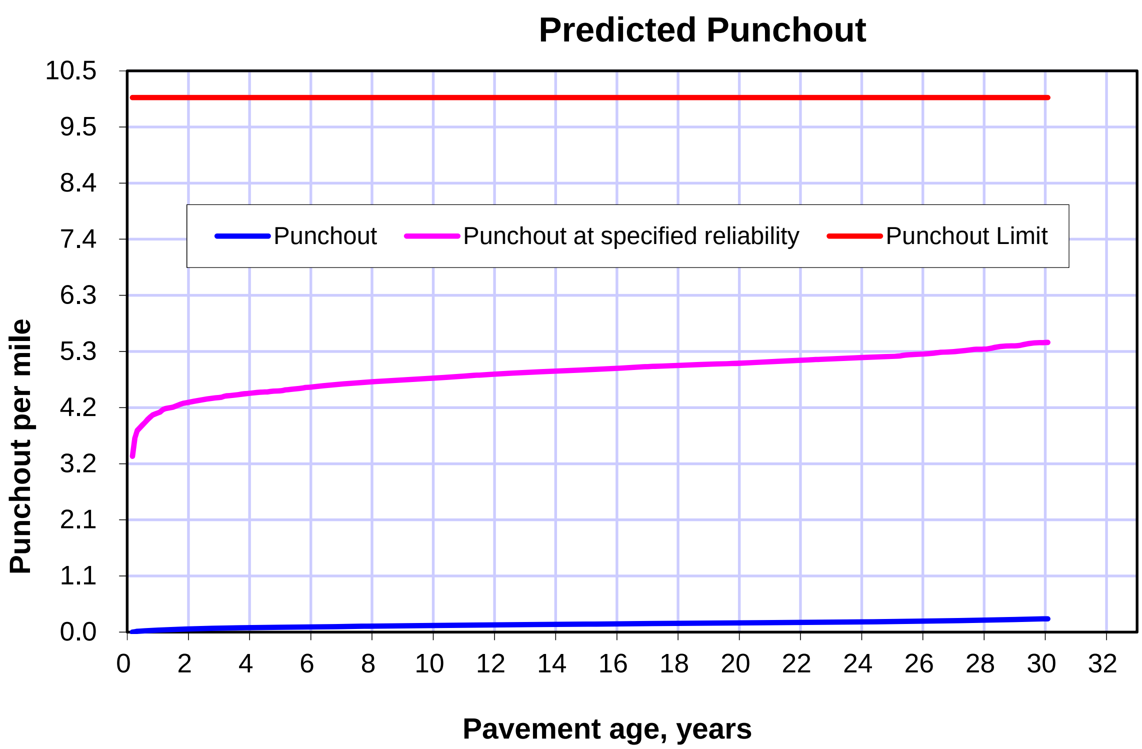



**Figure A.10 Predicted Punch out of Design 4**

**Table A.1 Performance of Design 4**

| Performance Criteria | Distress Target | Reliability Target | Distress Predicted | Reliability Predicted | Acceptable |
|---|---|---|---|---|---|
| Terminal IRI (in/miles) | 172 | 95 | 63.6 | 99.9 | Pass |
| CRCP Punchouts (per mi) | 10 | 95 | 0.2 | 99.9 | Pass |
| Maximum CRCP Crack Width (in) | 0.02 | | 0.0195 | | Pass |
| Minimum Crack Load transfer efficiency (LTE%) | 75 | | 82.3 | | Pass |

# Appendix B

(Sensitivity Analysis of Various Inputs of Deterministic Analysis of LCCA and Risk Analysis Results).

## Table B.1 Sensitivity Analysis of Various Parameters in Deterministic Approach

| Parameter | Value | Agency Costs Per Lane Mile (1000$) | | | | | User Costs Per Lane Mile (1000$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Design 1 | Design 2 | Design 3 | Design 4 | Trend | Design 1 | Design 2 | Design 3 | Design 4 | Trend |
| Discount Rate | 2 | $574 | $621 | $539 | $574 | | 22 | 22 | 23 | 4 | |
| | 2.5 | $568 | $613 | $531 | $573 | | 20 | 20 | 21 | 3 | |
| | 3 | $563 | $605 | $524 | $573 | | 19 | 19 | 20 | 3 | |
| | 3.5 | $558 | $598 | $518 | $573 | | 18 | 18 | 18 | 3 | |
| | 4 | $554 | $591 | $512 | $573 | | 17 | 17 | 17 | 2 | |
| | 4.5 | $550 | $585 | $507 | $572 | | 16 | 16 | 16 | 2 | |
| | 5 | $546 | $579 | $502 | $572 | | 15 | 15 | 14 | 2 | |
| | 5.5 | $542 | $574 | $497 | $572 | | 14 | 14 | 13 | 2 | |
| | 6 | $539 | $569 | $493 | $572 | | 13 | 13 | 12 | 2 | |
| | 6.5 | $536 | $565 | $489 | $572 | | 12 | 12 | 12 | 2 | |
| | 7 | $533 | $560 | $485 | $572 | | 12 | 12 | 11 | 1 | |
| Free Flow Capacity | 1500 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 1750 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 2000 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 2250 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 2500 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| Queue Dissipation Capacity | 1500 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $3 | |
| | 1600 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 1700 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 1800 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 1900 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 2000 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |

| Parameter | Value | Agency Costs Per Lane Mile (1000$) | | | | | User Costs Per Lane Mile (1000$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Design 1 | Design 2 | Design 3 | Design 4 | Trend | Design 1 | Design 2 | Design 3 | Design 4 | Trend |
| **Maximum Queue Length** | 1 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 2 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 5 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 10 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| **Work Zone Speed** | 30 | $554 | $591 | $512 | $573 | | $39 | $39 | $37 | $5 | |
| | 35 | $554 | $591 | $512 | $573 | | $30 | $30 | $29 | $4 | |
| | 40 | $554 | $591 | $512 | $573 | | $23 | $23 | $22 | $3 | |
| | 45 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 50 | $554 | $591 | $512 | $573 | | $11 | $11 | $12 | $2 | |
| **Work Zone Capacity** | 1200 | $554 | $591 | $512 | $573 | | $27 | $27 | $28 | $4 | |
| | 1300 | $554 | $591 | $512 | $573 | | $21 | $21 | $21 | $3 | |
| | 1400 | $554 | $591 | $512 | $573 | | $18 | $18 | $17 | $2 | |
| | 1415 | $554 | $591 | $512 | $573 | | $16 | $16 | $15 | $2 | |
| | 1600 | $554 | $591 | $512 | $573 | | $15 | $15 | $14 | $2 | |
| **Work Zone Length** | 1 | $554 | $591 | $512 | $573 | | $12 | $12 | $13 | $2 | |
| | 2 | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 3 | $554 | $591 | $512 | $573 | | $21 | $21 | $21 | $3 | |
| | 4 | $554 | $591 | $512 | $573 | | $26 | $26 | $25 | $4 | |
| **Working Hours** | 9AM-5PM | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 8AM-5PM | $554 | $591 | $512 | $573 | | $17 | $17 | $17 | $2 | |
| | 8AM-8PM | $554 | $591 | $512 | $573 | | $31 | $31 | $34 | $6 | |
| | 8PM-7AM, 11AM-4PM | $554 | $591 | $512 | $573 | | $5 | $5 | $4 | $1 | |
| | 24 Hours | $554 | $591 | $512 | $573 | | $22 | $22 | $25 | $4 | |
| | 8PM-8AM | $554 | $591 | $512 | $573 | | $0 | $0 | $0 | $0 | |

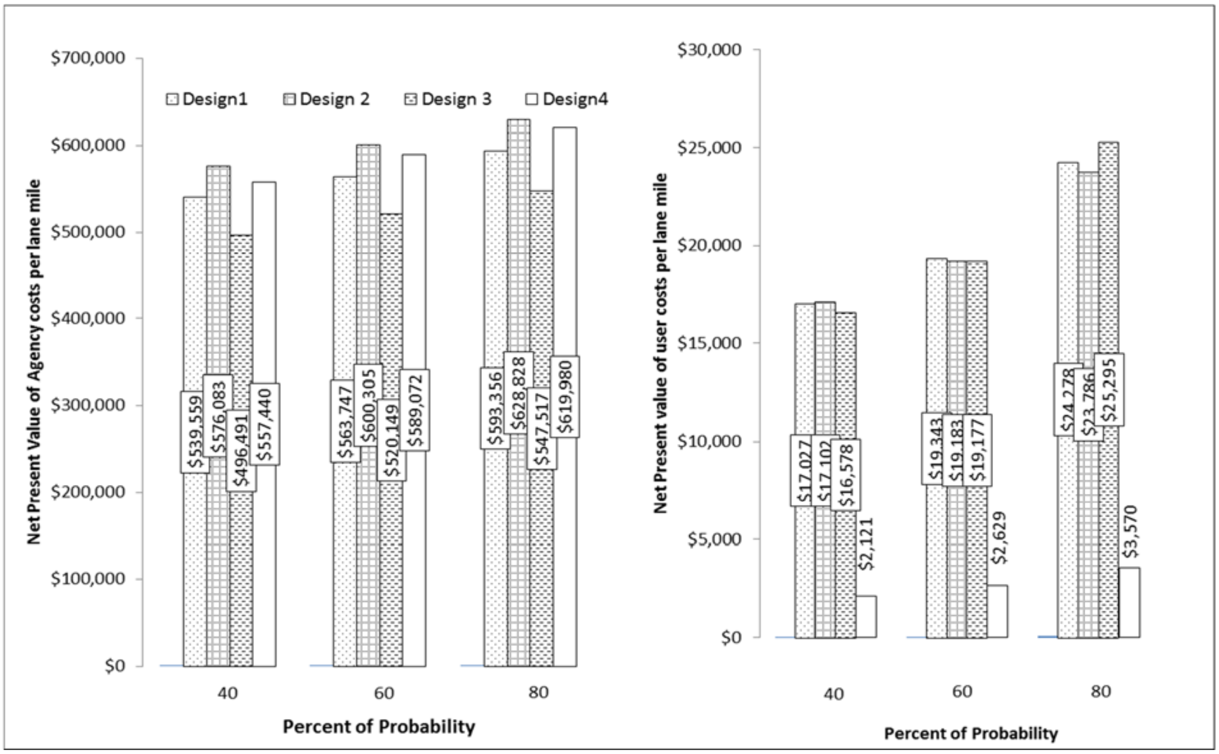



**Figure B.1 Net Present Value of Agency and User Costs at Various Percent of Probabilities**

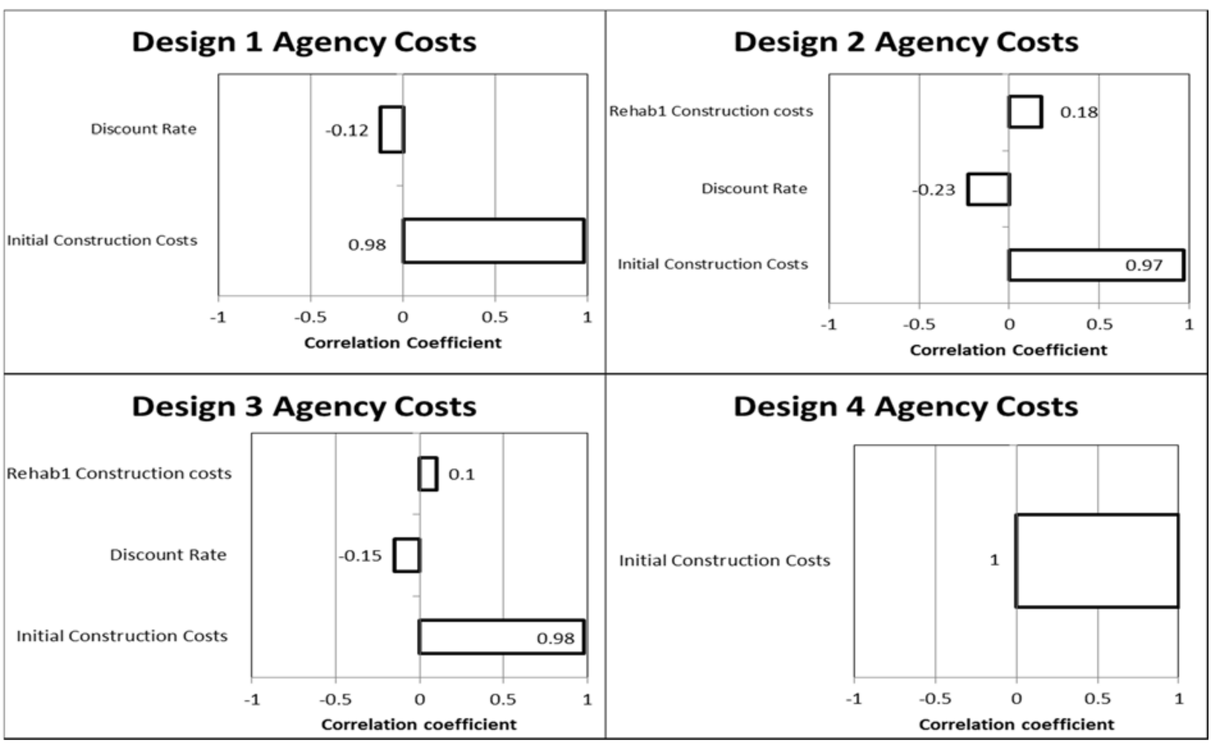



**Figure B.2 Correlation Sensitivity Plot for Net Present Value of Agency Costs**

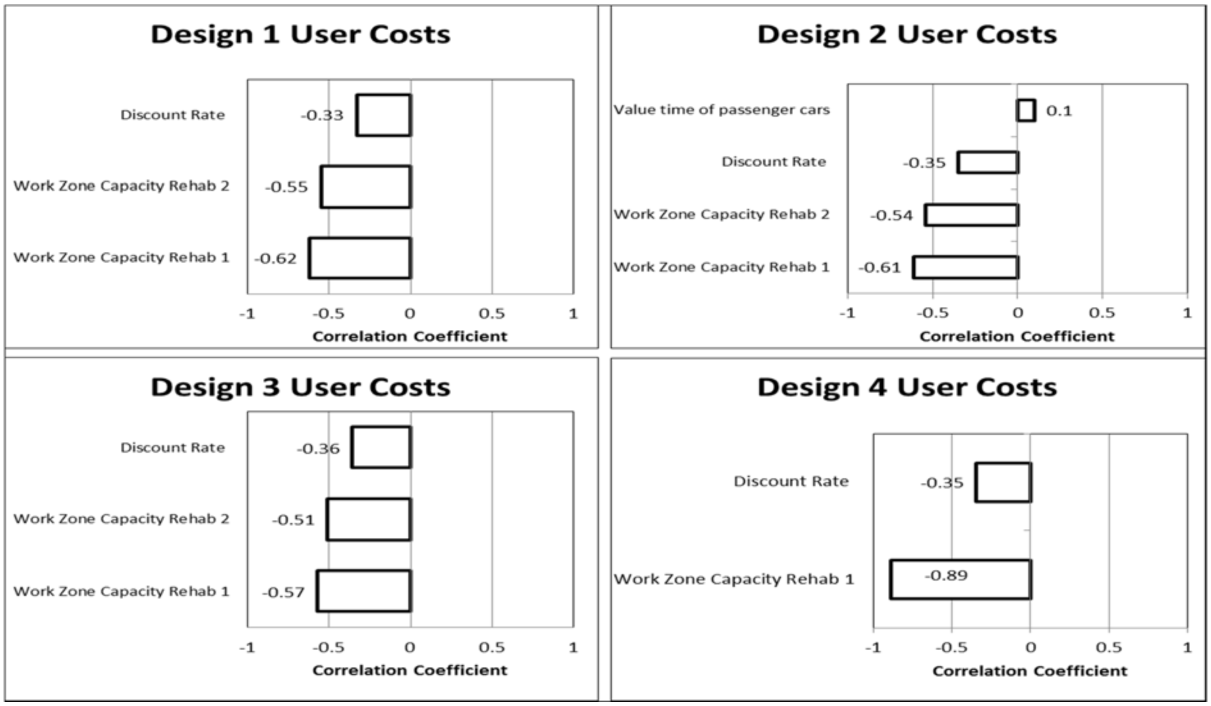



**Figure B.3 Correlation Sensitivity Plot for Net Present Value of User Costs**

## Appendix C

The material of this appendix, is a technical paper entitled "Necessity of Including Maintenance Traffic Delay Emissions in Life Cycle Assessment of Pavements", was presented in the International Conference on Sustainable Design, Engineering and Construction (ICSDEC 2016) held in Tempe, Arizona on 18-20 May 2016. The technical paper was published in the Journal of Procedia Engineering, Elsevier.

# Appendix.C. Necessity of Including Maintenance Traffic Delay Emissions in Life Cycle Assessment of Pavements

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## C.1. Abstract

The Life Cycle Assessment (LCA) is a method which aggregates the environmental impacts associated within the life cycle of a pavement. Incorporation of LCA has been mostly focused on the emissions produced in the construction phase and in its constituents, such as material extraction and manufacturing, hauling of materials, etc. Less emphasis has been given to emissions caused by traffic delays during maintenance operations due to lack of well-defined methodology and unfamiliarity about the magnitude of these emissions. In this study, an approach is proposed to include traffic delay emissions by combining Users Cost approach of Life Cycle Cost Analysis (LCCA) with Motor Vehicle Emissions Simulator (MOVES 2014) developed by the United States Environmental Protection Agency (US EPA). The LCA was performed for four different pavement designs and their Global Warming Potential (GWP) were included in the assessment. The GWP of the four designs with and without considering traffic delay emissions (in carbon dioxide equivalents: CO2e) were 53, 51, 50, and 22 versus 6.1, 4.5, 4.3, and 13 thousand tons per mile, respectively. The differences between the GWP with and without traffic delay emissions suggests that there is a need to include traffic delay emissions in the LCA to better estimate environmental impact.

## C.2. Introduction

Construction of highways requires a significant amount of natural resources, capital, workforce, etc., and pavement design drives these parameters. Pavements have significant potential to influence the environment, and economy. Hence, various alternate pavement designs needs to be developed and evaluated thoroughly from design to end of life. Over the years,

practitioners have proposed to utilize the Life Cycle Cost Analysis (LCCA) approach to appraise the costs associated with long-term highway usage, and the environmental impacts using the Life Cycle Assessment (LCA). The LCCA of pavements estimates the various costs in a pavement life cycle and converts the anticipated costs to present worth. LCCA helps to understand the economic efficiencies between various alternative designs. Many state highway agencies have implemented LCCA to analyze alternative designs (Rangaraju et al. 2008) to select the most economical design. Federal Highway Administration (FHWA) has developed a LCCA software product named RealCost2.5 to facilitate the numerical calculations in accordance with FHWA's best practice methods ("Life-Cycle Cost Analysis Software - Resources - Transportation Performance Management - Federal Highway Administration" 2015). The LCA, proposed by International Organization of Standards (ISO), is a tool that comprehensively quantifies environmental impacts throughout the life of a highway. Although the research in LCA is still developing, it has been in use to evaluate pavements for over a decade (Santero et al. 2011a). The LCA application studies have mainly focused on material extraction, production, transportation, and construction phases while ignoring the impacts caused by traffic delays during scheduled maintenance operations. The decisions that are made based on partial LCA may lead to wrong conclusions and it will be worse if the omitted sections in LCA have larger impacts on the overall environmental footprint of a pavement (Santero et al. 2011b).

### C.3. Literature Review

Impacts of traffic delays on the LCA have been analyzed by researchers over the years. Kendall et al. (2008) evaluated two alternate bridge deck designs and estimated that the construction traffic delays emissions caused 79% of the total emissions. Santero and Horvath (2009) analyzed eight components of various phases of the LCA namely: 1) material extraction and production, 2) transportation, 3) onsite equipment, 4) traffic delay, 5) concrete carbonation, 6) roadway lighting, 7) albedo, and 8) rolling resistance . They stated that components like traffic

delay emissions, lighting, location etc., are all context related factors and the impacts of a given component varies geographically.

Hanson et al. (2012) performed a study to determine the relative share of various components of the LCA of pavements including traffic delay emissions for a 50 year life time. The authors explicitly stated that the traffic disruption for this particular case study was minimal due to low traffic volume but, it can be a potential source of emissions for other cases. Similarly, the relative significance of work zone traffic delay emissions with respect to other phases in rural areas was done by Ting et al. and the study concluded that impacts due to work zone traffic were very small as compared to other processes in the LCA of pavements in rural areas.

It is apparent from the above studies that traffic delay emissions is context based, that is highways in rural areas, low traffic volume roads, and maintenance strategies that do not develop queues have a minimal impact on traffic delay emissions (Santero and Horvath 2009). On the other hand, in urban areas and highways with higher AADT, traffic delay emissions are significant and can surmount the other components of the LCA. Omitting emissions due to traffic delays in such cases may significantly undervalue the life cycle emissions (Walls and Smith 1998; Liu et al. 2014; Santero et al. 2011b). In summary, emissions from traffic delays can be substantial and have been overlooked in LCA of pavements due to the lack of practical tools and needs to be evaluated as more tools for evaluation become available and was focus of this study.

### C.4. Objectives

The following are the objectives formulated for this study:

- Develop a practical methodology for estimating emissions due to traffic delays using the best available tools and methodologies.
- Provide necessary information for decision makers in selecting the best designs and alternative maintenance strategies.

### C.5. Numerical Example

The need of this study is explained through an example. Four equivalent pavement designs were developed in this study. Equivalent design implies that each alternative was designed to perform equally, and provide the same level of service, over the same performance period (Stephanos,P.J 2008). The designs were developed based on the recommendations of the Texas Department of Transportation pavement design guide. Each of the design consisted of six-lane highway (three lanes on each side) and has an Annual Average Daily Traffic (AADT) of 61,236 on each side, as per 2014 traffic count. The traffic consists of 10.6% of trucks and 89.4% of passenger cars. The annual growth of traffic is assumed to be 0.75% and pavements were designed for 30 years. The four pavement designs varied in their material composition and thickness of layers. On average, designs 1, 2, and 3 had two rehabilitations during a 30 year period and the design 4 required a minor rehabilitation. For this study, it was assumed that the hauling distances of all raw materials as 50 miles to the plants and 12 miles from the plants to construction sites.

Greenhouse gas emissions were accounted during material extraction and manufacturing, transportation, and construction of various pavement designs. The materials and equipment required for maintenance operations were also included. The use and end of life phases of pavements were not considered. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) by Argonne National Laboratory (U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy) was employed to estimate the emissions from the material extraction and manufacturing phase as well as the transportation phase. Construction equipment emissions are drawn from EPA's NONROAD model (User Guide MOVES 2014). The type of equipment and working hours of equipment were estimated based on the RSMeans data (2012) for the El Paso Texas region. The inventory of greenhouse gases are characterized into Global Warming Potential (GWP) by transforming the greenhouse gases into carbon dioxide equivalents. The conversion factors were provided by EPA's impact assessment tool "Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI)". Initially the

Global Warming Potential (GWP) of the four designs was evaluated without considering the traffic delay emissions.

## C.6. Proposed Methodology

During maintenance of highways, the vehicles are subjected to different operating conditions like reduced speed, queuing, frequent braking etc., and these changes in vehicle operations cause's additional impacts on environment. These additional impacts can be captured by: 1) characterizing the traffic flows, 2) simulating the traffic, and 3) having a reliable data base for estimating emissions from vehicles under different working conditions. The Motor Vehicle Emission Simulator (MOVES) tool meets these requirements and was used in this study.

### C.6.1.1. Motor Vehicle Emission Simulator (MOVES 2014)

MOVES is developed by the U.S. Environmental Protection Agency (EPA) that provides an accurate estimate of emissions from highway vehicles to off-road mobile equipment under a wide range of user defined conditions ( User Guide MOVES 2014). The MOVES model includes a default database that summarizes emissions and relevant information for the entire United States ( User Guide MOVES 2014). The database utilizes the data from many sources, including EPA research studies, Census Bureau vehicle surveys, FHWA travel data, and other federal, state, local, industry and academic sources. Project level analysis was considered in this study as it is most suitable for analyzing alternate designs and, it comprises of two phases. In the first phase of modeling, general information and required inputs are affirmed such as vehicle types, time periods, geographical areas, pollutants, vehicle operating characteristics etc.

In the second phase, the "Project Data Manager" tool enables the user to enter specific data from the project into an input database. User-defined or project-specific details can be entered into input database. The primary inputs required are "Links" and "Link Source Types". A link in MOVES indicates the segment of road that is being modelled. "Links" requires nine inputs such as: Link Id (like inbound or outbound), County Id, Zone Id, Road Type, Link Length, Link Volume, Link Average Speed, Link Description, and Link Average Grade. "Link Source Types"

requires the following inputs: Link Id, Source Type (vehicles types) and Source Type Hour Fraction (percentage of each type of vehicles in traffic).

The important factor in estimating the emissions is to simulate the change in vehicle operation due to delays. In MOVES, there are three options of simulating traffic activity:

1. Average Speed: Assigning an average speed to vehicles in a link or roadway. This method accounts for less inputs. However, it is less precise as compared to the other methods.
2. Link Drive Schedule: The drive cycle for each link is required. Second by second variation in vehicles speed needs to be entered. It is more precise than the Average Speed method.
3. Opmode Distribution: This requires more detailed inputs such as start, stop, idling hours, parked fraction, acceleration, deceleration of vehicles, etc. It is the best method to simulate the actual traffic.

The proximity of the estimated emissions to those of real life emissions depends on accuracy of the inputs. In this study, Average Speed method was considered due to its simplicity in characterizing the traffic on the roadway.

#### C.6.1.2. Calculating Inputs for MOVES from Work Zone user Cost method in LCCA

The LCCA Work Zone user method is selected for generating inputs for MOVES 2014 for the following reasons:

- LCCA is a well-established method and it is being implemented by many state highway agencies for selecting alternate pavement designs. The software provided by FHWA to perform LCCA is based on FHWA's best practice methods ("Life-Cycle Cost Analysis Software - Resources - Transporation Performance Management - Federal Highway Administration" 2015).

- The LCCA has a well-defined methodology for estimating user costs due to delays; the same science can be used to generate the inputs for MOVES.
- LCCA and LCA are being integrated for analyzing the designs to address sustainability. Since both analyses need to make assumptions that may have significant influence, adapting the same methodology in both methods will reduce the number of assumptions.

The important factors for estimating user costs due to traffic delays are: projected AADT at the time of maintenance, hourly demand distributions, vehicle classification, work zone speed, vehicles speeds in case of queue formation, duration of lane closures, timing, work zone length, number and capacities of lanes during maintenance (Walls and Smith 1998). Similar inputs were required by MOVES for characterizing link and link source type, hence, the methodologies implemented in RealCost 2.5 LCCA software can be adapted for estimating emissions. The following steps demonstrate procedures for calculating the link length, speed and volume. The steps are in line with the work zone user costs estimates implemented in LCCA and explained by Walls and Smith (1998). The Design 1 and its first maintenance are explained in this methodology. One lane on each side is closed from 9AM—5PM, i.e., two lanes on both sides are open for traffic instead of three. Under normal conditions the highway speed is 60 miles per hour (MPH) whereas during maintenance it is reduced to 40 MPH over a 1 mile work zone distance.

Step 1: The future traffic is calculated using the following equation 1 (Walls and Smith 1998)

$$Future\ Year\ AADT = (Base\ Year\ AADT) \times (Vehicle\ Class\ \%) \times (1 + growth\ rate)^{(Future\ Yr - Base\ Yr)} \quad (1)$$

For the same traffic, the AADT in 2022 (8.3 years first maintenance from 2014) is expected to be 130,016.

Step 2: Hourly demand can be calculated using the following equation 2 (Walls and Smith 1998)

$$\text{Hourly Demand} = (\text{AADT})\ \text{X}\ (\text{Hourly Distribution Factor})\ \text{X}\ (\text{Hourly Directional Factor}) \quad (2)$$

Step 3: Table C.1 shows default hourly distributions for urban (columns a—d) from Micro BENCOST (James Walls and Michael R Smith 1998) which was used in this example. Using equations 1 and 2, the typical inbound and outbound traffic in 2022 is shown in column e and f of Table C.1.

Step 4: It is important to assume the capacity of a highway under various conditions during maintenance. If the demand is less than the capacity, no queue will form allowing traffic to freely flow. Once a queue develops, all approaching vehicles must not only slow down before proceeding through the work zone itself, but they also must stop at the upstream end of the queue and creep through the length of the physical queue under forced flow conditions (Walls and Smith 1998). Typically, during maintenance there will be three capacities:

I. The free flow capacity of the highway under normal operating conditions is considered to be 2,180 vehicles per hour (VPH) per lane in this study( as per Tables 3.4 to 3.6 of Walls and Smith (1998)).

II. Reduction in capacity of the highway when the work zone is in place is considered to be 1415 VPH per lane in this study (as per Figure 3.4 of Walls and Smith ( 1998)).

III. The capacity of the highway to dissipate traffic from a standing queue is considered to be 1818 VPH per lane in this study, as per the recommendations of Greenroads Manual and Walls and Smith (1998).

Step 5: In this step, the simplified method proposed by Walls and Smith (1998) was employed to calculate queue lengths. The method involves calculating the number of queued vehicles to the available lanes and multiplying the number of vehicles per lane by an assumed average vehicle length that includes the space between the vehicles. In this study, the distance between vehicles in the queue is assumed to be 30 feet in length.

Step 6: The speed of the vehicles in a queue can be determined by using a forced flow average speed versus a volume to capacity (v/c) ratio. Graphs for the level of service F are

contained in the earlier editions of the highway capacity manual as described by Walls and Smith(1998). When two lanes are open instead of three then the volume of highway will be 2,830 VPH (1,415X 2=2,830). The capacity of highway is 6,540 VPH (3 X 2,180)). The V/C ratio is 0.43 and the corresponding speed from Figure C.1, is 8 MPH. Even though all the lanes are open after maintenance, the existing queue cannot reach the free flow capacity instantly. Queue dissipates gradually and the speed during the transition can be calculated as mentioned above where the volume will be three times the queue dissipation capacity (1,818 X 3=5,454). The V/C ratio is 0.83 and the corresponding speed from Figure C.1, is 18 MPH.

**Table C.1 Default Hourly Distributions for Urban Area from Micro BENCOST**

| Hour (24-hr Clock) (a) | % ADT (b) | Inbound (c ) | Outbound (d) | Inbound in 2022 (e ) | Outbound in 2022 (f) |
|---|---|---|---|---|---|
| 0-1 | 1.2 | 47 | 53 | 734 | 828 |
| 1-2 | 0.8 | 43 | 57 | 448 | 593 |
| 2-3 | 0.7 | 46 | 54 | 419 | 492 |
| 3-4 | 0.5 | 48 | 52 | 312 | 338 |
| 4-5 | 0.7 | 57 | 43 | 519 | 392 |
| 5-6 | 1.7 | 58 | 42 | 1283 | 929 |
| 6-7 | 5.1 | 63 | 37 | 4182 | 2456 |
| 7-8 | 7.8 | 59 | 41 | 5989 | 4162 |
| 8-9 | 6.3 | 59 | 41 | 4837 | 3362 |
| 9-10 | 5.2 | 55 | 45 | 3722 | 3045 |
| 10-11 | 4.7 | 46 | 54 | 2814 | 3303 |
| 11-12 | 5.3 | 49 | 51 | 3380 | 3518 |
| 12-13 | 5.6 | 50 | 50 | 3644 | 3644 |
| 13-14 | 5.7 | 50 | 50 | 3709 | 3709 |
| 14-15 | 5.9 | 49 | 51 | 3762 | 3916 |
| 15-16 | 6.5 | 46 | 54 | 3891 | 4568 |
| 16-17 | 7.9 | 45 | 55 | 4627 | 5655 |
| 17-18 | 8.3 | 45 | 55 | 4861 | 5941 |
| 18-19 | 5.9 | 46 | 54 | 3532 | 4146 |
| 19-20 | 3.9 | 48 | 52 | 2436 | 2639 |
| 20-21 | 3.3 | 47 | 53 | 2019 | 2276 |
| 21-22 | 2.8 | 47 | 53 | 1713 | 1931 |
| 22-23 | 2.3 | 48 | 52 | 1437 | 1557 |
| 23-24 | 1.7 | 45 | 55 | 996 | 1217 |

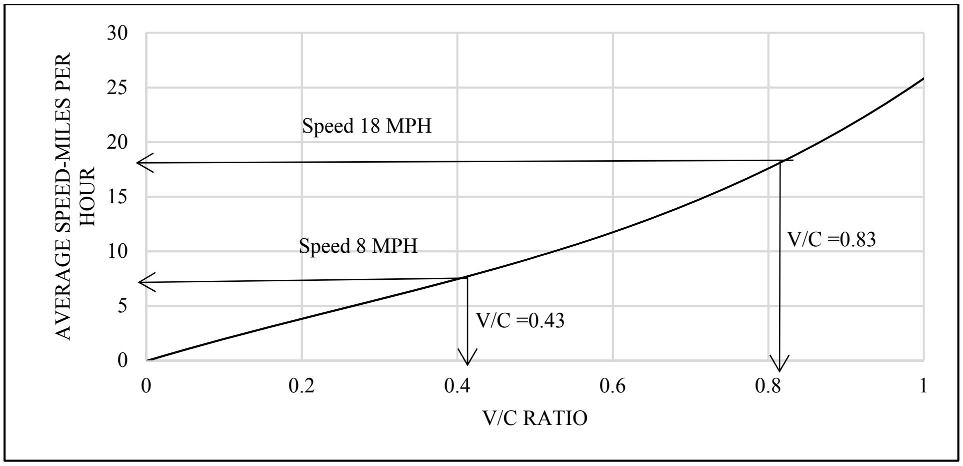


**Figure C.1 Average Speed versus V/C Ratio (Adapted from Walls and Smith (1998))**

The Table C.2 shows the queue lengths estimation, queue speed, and VPH that cross the queue length. It is evident that once one lane on each side of the highway closes from 9AM—5PM, queue begins to form starting at 9AM and extends up to 9PM (shaded area in the table). For brevity, inbound calculations for hours 9 and 10 are discussed. The inbound traffic at 9AM is 4,837 vehicles and capacity is only 2,830 (2 X 1, 415), which leads to 2,007 queued vehicles. The inbound traffic at 10AM was 3,722 vehicles, however, 2,007 vehicles were already in queue, so the total demand increases to 5,729 (3,722 plus 2,007). The capacity is 2,830, so the total vehicles queued by the end of hour is around 2,899 (5,729-2,830). By the end of the 9AM hour, the queue length is 2,007 times 30 feet which is around 5.7 miles and work zone length is 1 mile. The total link length is 5.7 miles plus 1 mile which yields a total of 6.7 miles. The total number of vehicles in the total link 4,837. The average speed is considered as 8 MPH.

The impacts from traffic delays are measured as the difference between emissions with and without maintenance.

Table C.3 shows the summarized output for two pollutants (carbon dioxide ($CO_2$), and methane ($CH_4$)) in grams. The additional impact due to maintenance for the present scenario is 3,356 x 106 grams of $CO_2$, and 3.0 x 108 grams of $CH_4$ per day. The total impact due to maintenance depends on the total days of maintenance.

## Table C.2 Estimation of Queue Length, Queue Speed and Vehicles/Hour

| Time (a) | Demand | | Lanes Open (d) | Capacity (e) | Queue Rate | | No of Vehicles Queued | | Inbound | | | | Outbound | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Inbound (b) | Outbound (c) | | | Inbound (f) | Outbound (g) | Inbound (h) | Outbound (i) | Queue Speed (j) | Queue length (k) | Inbound link length(j+k) (l) | Vehicles per hour (VPH) (m) | Queue Speed (n) | Queue length (o) | Outbound Link Length (n+o) (p) | Vehicles per hour (VPH) (q) |
| **1** | 734 | 828 | 3 | 6540 | -5806 | -5712 | 0 | 0 | 60 | 0.00 | 1.00 | 734 | 60 | 0.00 | 1.00 | 828 |
| **2** | 448 | 593 | 3 | 6540 | -6092 | -5947 | 0 | 0 | 60 | 0.00 | 1.00 | 448 | 60 | 0.00 | 1.00 | 593 |
| **3** | 419 | 492 | 3 | 6540 | -6121 | -6048 | 0 | 0 | 60 | 0.00 | 1.00 | 419 | 60 | 0.00 | 1.00 | 492 |
| **4** | 312 | 338 | 3 | 6540 | -6228 | -6202 | 0 | 0 | 60 | 0.00 | 1.00 | 312 | 60 | 0.00 | 1.00 | 338 |
| **5** | 519 | 392 | 3 | 6540 | -6021 | -6148 | 0 | 0 | 60 | 0.00 | 1.00 | 519 | 60 | 0.00 | 1.00 | 392 |
| **6** | 1283 | 929 | 3 | 6540 | -5257 | -5611 | 0 | 0 | 60 | 0.00 | 1.00 | 1283 | 60 | 0.00 | 1.00 | 929 |
| **7** | 4182 | 2456 | 3 | 6540 | -2358 | -4084 | 0 | 0 | 60 | 0.00 | 1.00 | 4182 | 60 | 0.00 | 1.00 | 2456 |
| **8** | 5989 | 4162 | 3 | 6540 | -551 | -2378 | 0 | 0 | 60 | 0.00 | 1.00 | 5989 | 60 | 0.00 | 1.00 | 4162 |
| **9** | 4837 | 3362 | 2 | 2830 | 2007 | 532 | 2007 | 532 | 8 | 5.70 | 6.70 | 4837 | 8 | 1.01 | 2.01 | 2684 |
| **10** | 3722 | 3045 | 2 | 2830 | 892 | 215 | 2900 | 747 | 8 | 8.24 | 9.24 | 5730 | 8 | 1.41 | 2.41 | 3683 |
| **11** | 2814 | 3303 | 2 | 2830 | -16 | 473 | 2883 | 1220 | 8 | 8.19 | 9.19 | 5713 | 8 | 2.31 | 3.31 | 4742 |
| **12** | 3380 | 3518 | 2 | 2830 | 550 | 688 | 3433 | 1908 | 8 | 9.75 | 10.75 | 6263 | 8 | 3.61 | 4.61 | 8345 |
| **13** | 3644 | 3644 | 2 | 2830 | 814 | 814 | 4247 | 2722 | 8 | 12.07 | 13.07 | 7077 | 8 | 5.16 | 6.16 | 12571 |
| **14** | 3709 | 3709 | 2 | 2830 | 879 | 879 | 5126 | 3601 | 8 | 14.56 | 15.56 | 7956 | 8 | 6.82 | 7.82 | 11850 |
| **15** | 3762 | 3916 | 2 | 2830 | 932 | 1086 | 6059 | 4687 | 8 | 17.21 | 18.21 | 8889 | 8 | 8.88 | 9.88 | 12149 |
| **16** | 3891 | 4568 | 2 | 2830 | 1061 | 1738 | 7120 | 6425 | 8 | 20.23 | 21.23 | 9950 | 8 | 12.17 | 13.17 | 13726 |
| **17** | 4627 | 5655 | 2 | 2830 | 1797 | 2825 | 8917 | 9250 | 8 | 25.33 | 26.33 | 11747 | 8 | 17.52 | 18.52 | 15952 |
| **18** | 4861 | 5941 | 3 | 5454 | -593 | 487 | 8324 | 9737 | 18 | 15.76 | 16.76 | 13778 | 18 | 18.44 | 19.44 | 15191 |
| **19** | 3532 | 4146 | 3 | 5454 | -1922 | -1308 | 6402 | 8429 | 18 | 12.12 | 13.12 | 11856 | 18 | 15.96 | 16.96 | 13883 |
| **20** | 2436 | 2639 | 3 | 5454 | -3018 | -2815 | 3384 | 5615 | 18 | 6.41 | 7.41 | 8838 | 18 | 10.63 | 11.63 | 11069 |
| **21** | 2019 | 2276 | 3 | 6540 | -4521 | -4264 | 0 | 1351 | 60 | 0.00 | 1.00 | 2019 | 18 | 2.56 | 3.56 | 6805 |
| **22** | 1713 | 1931 | 3 | 6540 | -4827 | -4609 | 0 | 0 | 60 | 0.00 | 1.00 | 1713 | 60 | 0.00 | 1.00 | 1931 |
| **23** | 1437 | 1557 | 3 | 6540 | -5103 | -4983 | 0 | 0 | 60 | 0.00 | 1.00 | 1437 | 60 | 0.00 | 1.00 | 1557 |
| **24** | 996 | 1217 | 3 | 6540 | -5544 | -5323 | 0 | 0 | 60 | 0.00 | 1.00 | 996 | 60 | 0.00 | 1.00 | 1217 |

## Table C.3 Output Emissions from MOVES 2014 for Design 1 First Maintenance

| HOUR | Carbon dioxide (grams) | | | Methane (grams) | | |
|---|---|---|---|---|---|---|
| | Maintenance (9am-5pm) (a) | No Maintenance (b) | Additional impact (a-b) | Maintenance (9am-5pm) (e) | No Maintenance(f) | Additional impact (e-f) |
| **1** | 1192663 | 1192663 | 0 | 7 | 7 | 0 |
| **2** | 790123 | 790123 | 0 | 5 | 5 | 0 |
| **3** | 687210 | 687210 | 0 | 4 | 4 | 0 |
| **4** | 487895 | 487895 | 0 | 3 | 3 | 0 |
| **5** | 680013 | 680013 | 0 | 4 | 4 | 0 |
| **6** | 1642540 | 1642540 | 0 | 10 | 10 | 0 |
| **7** | 4914832 | 4914832 | 0 | 30 | 30 | 0 |
| **8** | 7615924 | 7615924 | 0 | 46 | 46 | 0 |
| **9** | 51644808 | 6265579 | 45379229 | 576 | 37 | 539 |
| **10** | 85501138 | 5263809 | 80237329 | 931 | 31 | 900 |
| **11** | 99259850 | 4808629 | 94451221 | 1065 | 28 | 1037 |
| **12** | 163729536 | 5476490 | 158253046 | 1734 | 28 | 1706 |
| **13** | 260169444 | 5833932 | 254335512 | 2726 | 34 | 2692 |
| **14** | 306428904 | 5976728 | 300452176 | 3183 | 35 | 3148 |
| **15** | 331441492 | 6204627 | 325236865 | 3430 | 36 | 3394 |
| **16** | 373447640 | 6841076 | 366606564 | 3860 | 39 | 3821 |
| **17** | 436090664 | 8305324 | 427785340 | 4515 | 48 | 4467 |
| **18** | 638899312 | 8697225 | 630202087 | 4887 | 51 | 4836 |
| **19** | 490603080 | 6136956 | 484466124 | 3780 | 35 | 3745 |
| **20** | 192417632 | 4014748 | 188402884 | 1872 | 23 | 1849 |
| **21** | 3368249 | 3368249 | 0 | 19 | 19 | 0 |
| **22** | 2840501 | 2840501 | 0 | 17 | 17 | 0 |
| **23** | 2322135 | 2322135 | 0 | 8 | 8 | 0 |
| **24** | 1709177 | 1709177 | 0 | 10 | 10 | 0 |
| **Cumulative** | | | 3355808377 | | | 32134 |

### C.7. Influence of Maintenance Timing on Emissions

The timing of maintenance effects the traffic delay emissions. To reveal the importance of timing of maintenance, the GWP for various pavement maintenance strategies was estimated for four different scenarios (column b of Table 4). The time period from 9AM —5PM was considered to reflect maintenance during peak hours. 10PM — 6AM was considered to reflect maintenance during nights. The time period from 11AM —3PM and 8PM — 12AM was considered to reflect maintenance during non-peak hours. The GWP estimated for various scenarios are summarized in Figure C.2, and Table C.4. It is evident that traffic delay emissions will be dominating factor if maintenance happens during peak hours (scenario 2 and 3) and overshadows other phases of LCA, and vice versa during non-peak hours (scenario 3). Further analysis reveals that when emissions due to delays are not considered in LCA the prominent environmental impact is due to material extraction. The GWP is around 65-75 % due to material extraction, if traffic delays are ignored in analysis. If maintenance during peak hours of traffic is considered in LCA then GWP due to material extraction phase shifted to 5-10% from 65-75% percentages. These differences demonstrate the significance of traffic delays emissions in LCA of pavements.

**Table C.4 Influence of Maintenance Timing on GWP**

| SNO (a) | Scenario (b) | Highest GWP per mile (1000 tons $CO_2e$) | | | Lowest GWP per mile (1000 tons $CO_2e$) | | | Difference in GWP (Highest vs Lowest) (i) |
|---|---|---|---|---|---|---|---|---|
| | | Design (c) | GWP (d) | Dominating Phase (e) | Design (f) | GWP (g) | Dominating Phase (h) | |
| **1** | No traffic delay emissions | 4 | 13.03 | Material Extraction (66%) | 3 | 4.30 | Material Extraction (66%) | 8.73 |
| **2** | Lanes closed from 9AM—5PM | 1 | 52.45 | Traffic Delay Emission (88%) | 4 | 21.81 | Material Extraction (55%) | 30.64 |
| **3** | Lanes closed from 10PM—6AM | 4 | 13.03 | Material Extraction (66%) | 3 | 4.33 | Material Extraction (66%) | 8.7 |
| **4** | Lanes closed from 11AM—3PM and 8PM—12 AM | 1 | 18.39 | Traffic Delay Emission (67%) | 4 | 15.77 | Material Extraction (76%) | 2.62 |

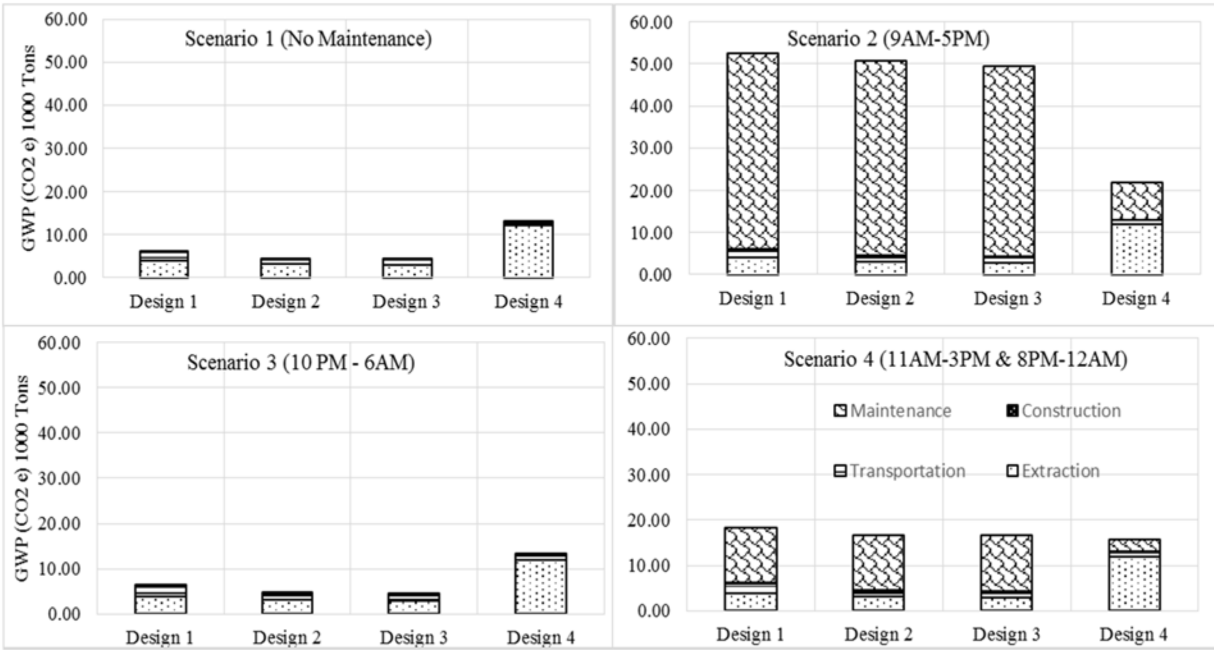


**Figure C.2 GWP of Alternative Designs for Different Maintenance Scenarios**

## C.8. Conclusions and Recommendations

The proposed methodology can be implemented to estimate traffic delay emissions by agencies during their selection of pavement designs. Since state highway agencies are familiar with LCCA methodology, the required inputs for MOVES can be easily obtained. Additionally, MOVES 2014 is a reliable simulation tool, which is regularly updated and is available at no cost.

Emissions during traffic delays can surmount the emissions due to other phases and the needs to be considered during the design and planning phases of a project. Although maintenance related emissions can significantly influence carbon footprint, the assumptions made in the LCA analysis should be followed. For instance, if design 3 was selected for construction and assumed that the maintenance will be performed during night hours, then the actual maintenance should be executed during night hours otherwise the benefit of selecting design 3 will be compromised. All possible scenarios should be evaluated and scenarios should be corresponding to the actual maintenance operations.

This study assumed that traffic cannot be re-routed and has to bypass the work zone. Further research for estimating AADT considering traffic diversion is required. Vehicles were assumed to travel at a uniform speed in the queues but, in reality vehicles are subjected to numerous modes such as stop, start, accelerate, decelerate etc. Future research in developing models to simulate future traffic movements during maintenance considering the various modes are required.

The authors of this study are aware that the proposed methodology yielded simple estimates of possible future emissions and that the actual emissions will differ. In accordance with Santero and Horvath (2009), the uncertainties prevail in estimates, but it may still be beneficial to understand the scope of potential impacts for each life cycle components. Estimate the benefits and drawbacks of various maintenance schedules before performing LCA.

The LCA comprises of many environmental and social factors and the selection of pavement design may change than what was observed in this study. Although various regular maintenance do occur on selected design types or premature failure occurs, it was not considered due to lack of data available.

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# Appendix D

The material of this appendix, is a technical paper entitled "An Approach for Performing Life Cycle Impact Assessment of Pavements for Evaluating Alternative Pavement Designs" , was presented in the International Conference on Sustainable Design, Engineering and Construction (ICSDEC 2016) held in Tempe, Arizona on 18-20 May 2016. The technical paper was published in the Journal of Procedia Engineering, Elsevier.

## Appendix.D. An Approach for Performing Life Cycle Impact Assessment of Pavements for Evaluating Alternative Pavement Designs

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### D.1. Abstract

Life Cycle Assessments (LCA) of pavements is currently used to compare alternate designs by appraising the environmental impacts. Life Cycle Impact Assessment (LCIA) is a key step in LCA, which models the emissions inventory into meaningful environment and human impacts. Although LCIA consists of four steps (classification, characterization, normalization, and weighting), most of the pavements LCA have been performed without normalization and weighting steps due to subjectivity involved. Normalization aims to associate impacts of a design to a set of reference values that is recognizable and understandable by the decision makers. The decisions made without considering normalization may lead to least sustainable pavement design. The objective of this study is to expand pavement LCA by including normalization and weighting in the process by proposing normalization and weighting approaches that will help in selecting sustainable pavement structure. To achieve objective of this study, LCA was performed on four equivalent pavement designs by estimating emissions for each pavement design for 30 years using various LCA datasets. The estimated emissions were further classified and characterized into various impact categories. External and internal normalization were performed on the characterized data. External normalization was performed using two reference systems US per capita emissions in 2008 and an average passenger car emissions. External normalization helps in understanding the magnitude of impacts due to a pavement as well as in differentiating the alternatives. Internal normalization assists in only comparing alternatives and needs no reference

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system. Based on the evaluation, it is proposed to use normalization and weighting for performing LCA of pavements.

*Keywords:* Life Cycle Assessments; Normalization; Weighting; Global Warming Potential; Emissions.

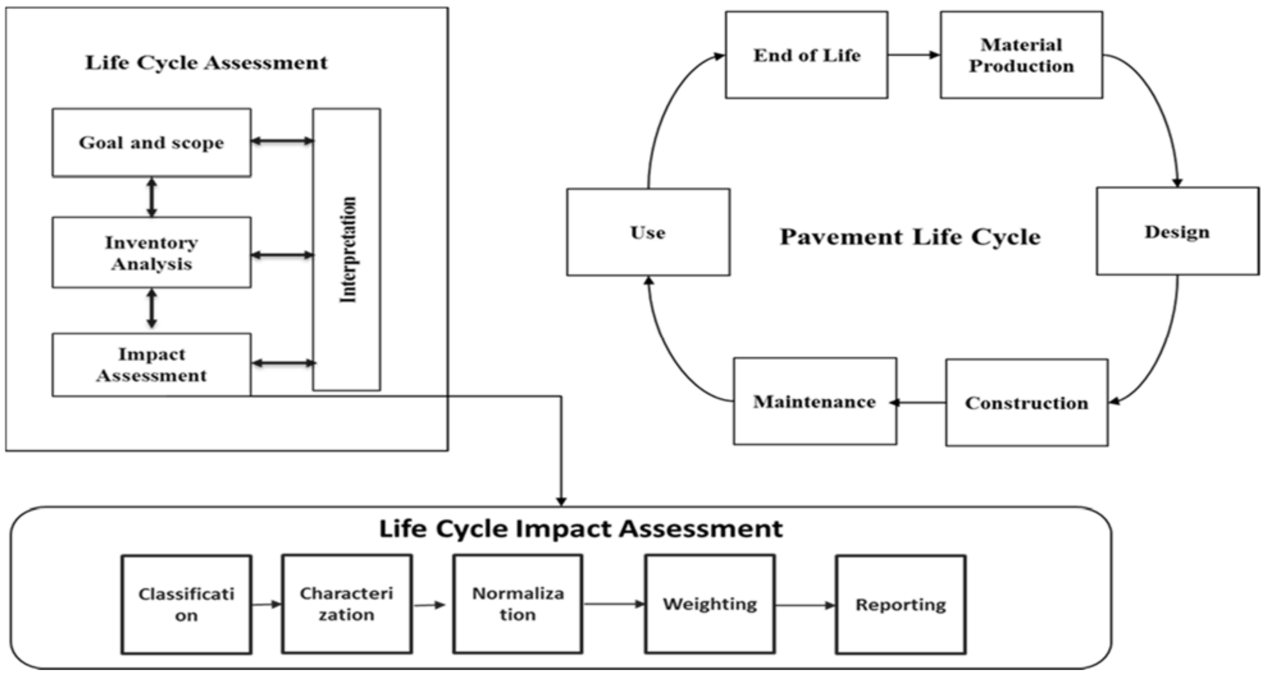
## D.2. Introduction

Increased importance towards sustainability has led many state highway agencies to incorporate sustainability principles into decision-making process. Construction and maintenance of pavements influences the life of people and environment surrounding them. Although various practices and factors influence the pavement designs selection, the most quantifiable factors include the cost, materials, equipment, and construction practices.

Researchers have proposed to evaluate environmental impacts of alternate pavement designs using Life Cycle Assessment (LCA) approach (Santero et al. 2011a). LCA comprehensively quantifies the emissions and energy flows of a product (pavement) in its Life Cycle. International organization of standardization (ISO) released two standards ISO-14040 2006 and ISO-14044 2006 to standardize the LCA methodology. Similar to ISO standards, detailed procedure for conducting of LCA has been proposed by United States Environment Protection Agency (US EPA) document (SAIC 2006). Even though LCA has been proposed by these agencies, they do not specifically provide guidance for performing LCA of pavements (FHWA TechBrieft 2014).

Various researchers have performed pavement LCA [(Weiland and Muench 2010), (Nisbet and others 2000), (Vidal et al. 2013), (Tatari et al. 2012), (Mroueh 2000), (Liu et al. 2014), (Santero et al. 2011b), (Huang et al. 2009b), (Barandica et al. 2013), (Anastasiou et al. 2015), (Thiel and Len 2014)] based on ISO standards. The consensus phases of LCA and life cycle of pavement are shown in Figure D.1. Although proposed phases of LCA suggests Life Cycle Impact Assessment, the studies mainly focused on estimating the emissions inventory by collecting data from numerous sources. Additionally, studies devoted significant time in accounting the emissions from all phases of pavements while placing little or no emphasis on impact assessment. It is essential for decision

makers to understand the true sense of the characterized impacts because these numbers will be used in selecting a design. Aggregated impact categories or emission inventories may be better interpreted by placing them in an adequate environment context (Sleeswijk et al. 2008). The normalization and weighting steps of LCIA aims at addressing these issues and is focus of this




study.

**Figure D.1 Framework for LCA, LCIA and Pavement Life Cycle**

## D.3. Objectives

The principle of normalization is to associate the characterized results of pavement to a common scale that is familiar and understandable to decision makers. The drawback of disregarding the normalization step in the LCIA is that the decision makers may place unnecessary importance on insignificant data leading to making inappropriate choices (Rogers and Seager 2009). Ultimately, all the efforts placed on conducting LCA will be futile if the decision makers chose an inappropriate design. Considering the importance of normalization in LCA, this study proposes to address the following objectives:

- To shed light on the importance of normalization in LCA of pavements and to examine the factors to be considered in selection of reference system.
- Evaluate various normalization procedures and guide the analysts in selecting suitable approach.

A light emphasis on weighting step in LCIA is also discussed, due to the interrelation between weighting and normalization. Since this study is aimed at pavement selection, the total analysis is presented as a case study for selection of a pavement design from four equivalent designs shown in Figure D.2 Alternative Pavement Designs (design1 (D1), design2 (D2), design3 (D3) and design 4 (D4)). The case study is chosen to just to envision the various stages of LCA and LCIA.

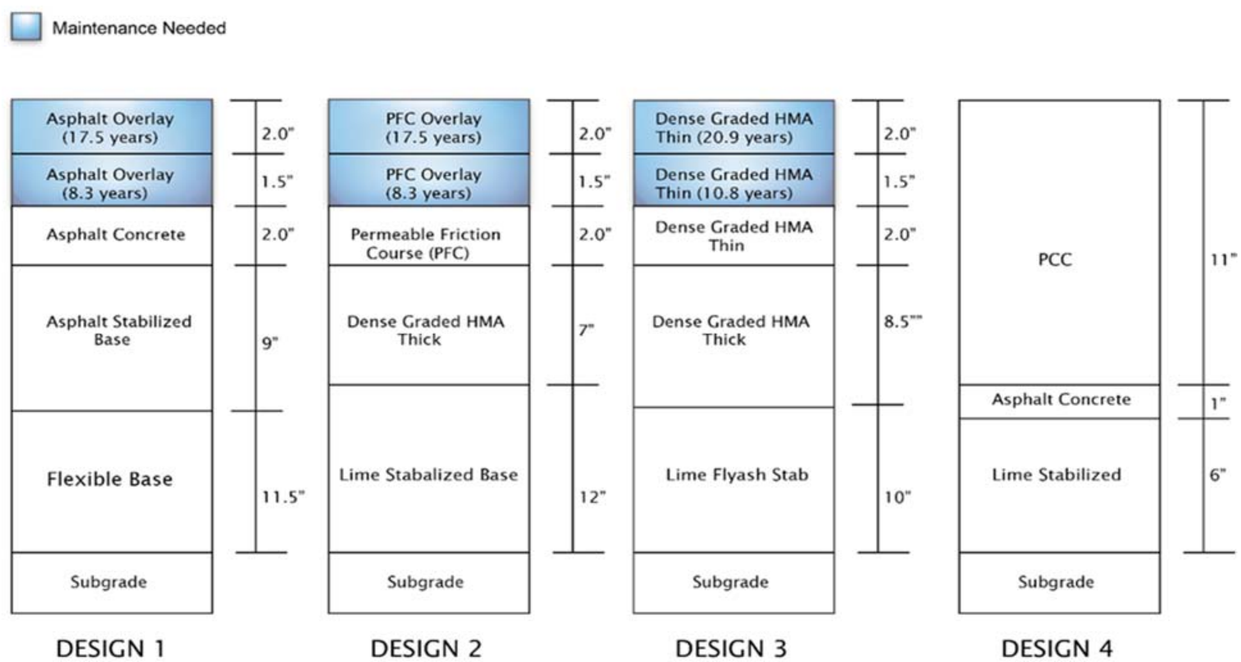



**Figure D.2 Alternative Pavement Designs**

## D.4. Approach

To perform LCA, the steps shown in Fig. 1 were performed including normalization and weighting steps of LCIA. The following sections explain in detail the approach adapted in this study.

### D.4.1. Goal and Scope of LCA

The goal of the present study is to assist decision makers in selecting structural designs of pavements which produces minimal environmental impact. Typically, a pavement life cycle consists of different phases such as material extraction and production, design, construction, maintenance, use, and end of life as shown in Figure D.1. A complete LCA study should include emissions from all these phases. However, Use phase, End of life phase and equipment manufacture emissions were not included in this study. The goal of this study is to differentiate various pavement designs and there are no well-established models that can assess the emissions from various pavement surfaces during use phase. Even though rolling resistance was used by Santero et al. (2011 b), there are uncertainty in the predicting models, and hence, use phase is ignored in this study. End of life poses a unique burden on the environment but, for pavements especially high volume highways, there is no well-defined end of life where the pavement would be removed and thrown away (Weiland and Muench 2010). In addition, emissions due to manufacturing of construction equipment were not considered because the construction equipment has a substantial life and allotting the manufacturing emissions for a particular project will be in appropriate.

### D.4.2. Life Cycle Inventory

In inventory phase, data is collected based on goal and scope definition. In this study, a process approach LCA was employed to account for various emissions during material extraction and manufacturing, transportation, and construction of alternative pavement designs. In process approach, the inputs and emissions for each discrete process within a life cycle system boundary are quantified rather than reference values obtained from the published literature. In this study, various inventory models were selected based on the reliability of emission data and feasibility to employ in pavement LCA and are discussed in the following paragraphs. Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) life cycle model was employed to estimate the emissions from the material extraction and manufacturing phase as well

as the transportation phase. GREET models provide upstream life cycle emissions for all fuels and the majority of the construction materials. In the GREET model, the user can develop their own processes or can modify existing processes for estimating emissions to replicate the actual process. For this study, a hauling distances 50 miles to the plants and 12 miles from plants to construction site were assumed for all materials (cement, asphalt, aggregates, diesel etc.).

The traffic delay emissions during maintenance operations were estimated using Motor Vehicle Emission Simulator (MOVES) 2014. It was also assumed that maintenance happens from 9AM—5PM and one lane on each side of pavement was closed. Emissions due to traffic delays during initial construction and emergency maintenances were not considered in this study. Construction equipment emissions during operation are drawn from the EPA's NONROAD model which is embedded in MOVES 2014 (US EPA 2014). The type of equipment and working hours of equipment were estimated based on the RSMeans data (2012) for the El Paso, Texas, region. The inventory data of various pollutants for the four pavements shown in Figure D.2, are displayed in the Table D.1.

**Table D.1 LCI of Four Pavement Designs/Mile Length**

| Pollutant | Design 1 | Design 2 | Design 3 | Design 4 |
|---|---|---|---|---|
| Carbon Monoxide (CO) in tons | 8.7E+01 | 8.1E+01 | 7.6E+01 | 3.3E+01 |
| Nitrogen Oxides ($NO_x$) in tons | 8.5E+01 | 5.9E+01 | 5.9E+01 | 2.8E+01 |
| Particle Matter (PM10) in tons | 5.9E+00 | 4.0E+00 | 3.9E+00 | 4.0E+00 |
| Particle Matter (PM 2.5) in tons | 1.9E+00 | 2.0E+00 | 1.7E+00 | 1.6E+00 |
| Sulfur Oxides ($SO_x$) in tons | 5.4E+00 | 3.3E+00 | 3.3E+00 | 2.1E+01 |
| Methane (CH4) in tons | 2.2E+01 | 1.5E+01 | 1.4E+01 | 7.6E+00 |
| Nitrous Oxide ($N_2O$) in tons | 5.1E-01 | 4.3E-01 | 3.7E-01 | 2.5E-01 |
| Carbon Dioxide $CO_2$ in tons | 5.2E+04 | 5.0E+04 | 4.9E+04 | 2.2E+04 |
| Sulfur Dioxide ($SO_2$) in tons | 5.2E+00 | 2.6E+00 | 2.9E+00 | 1.3E+00 |

### D.4.3. Life Cycle Impact Assessments

In the impact assessment phase, inventory data should be modeled into impacts. The impact assessment consists of the following steps: classification, characterization, normalization and weighting. In classification, step inventory results are assigned to relevant impact categories. For example, carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and other hydrofluorocarbons (HFCs) etc., contribute towards impact category designated as the Global Warming Potential (GWP). Hence, the available emissions are classified into groups based on their impact category.

The next step is to convert the classified inventory of each impact indicator into an equivalent scale. For example, various emissions that are contributing towards GWP could be transformed into carbon dioxide equivalents ($CO_2e$). The process of converting various pollutants in an impact category to a common scale is called characterization in LCIA and the factors required to transform the emissions are called characterization factors. These conversion factors are typically provided by the EPA's impact assessment Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) that strives in attaining consistency in environmental decision-making. Table D.2 displays the characterization factors for various impact categories namely: Global Warming Potential (GWP), Eutrophication (EUT), Smog (SMOG), Acidification (ACID), and Human Health Criteria Air Pollutants (HHCR). Even though there are other impact categories, the inventory data corresponds to the selected impact categories. The aggregate of impacts are then calculated for the inventory in Table D.1 (with respective characterized factors shown in Table D.2) and is summarized in Table D.3. The characterized data can be better understand through normalization and is explained in the following section.

#### D.4.3.1. Normalization

Normalization relates the aggregated impact categories of an LCA to the macro world in which the service / product is surrounded (Lindeijer 1996). Generally, normalization is a process of converting different numbers into common unit numbers. The purpose of the normalization is

to associate the characterized impacts of a design to a set of reference values that is recognizable and understandable by the decision makers. The advantages of normalization step in LCIA are:

a. It aids decision makers in understanding the characterized impact data.
b. It makes easier to make comparisons between impact scores of different impact categories (Norris 2001).
c. It expresses the relative magnitude of the impact scores on a scale that is common to all the categories of impact (Hauschild et al. 2003).
d. It serves as a means for preparation of weighing, which is the final step in LCIA (ISO/TR 14047: 2003).

**Table D.2 Characterized and Normalized Factors**

| **Characterization Factors**3 | | | | | |
|---|---|---|---|---|---|
| | **GWP kg CO2-eq/kg** | **EUT kg N-eq/kg** | **SMOG kg Nox-eq/kg** | **ACID kg H+eg/kg** | **HHCR kg milli-DALYS/kg** |
| **VOC** | **-** | - | 3.595 | - | |
| **CO** | **-** | - | 0.055 | - | 0.0003 |
| **Nox** | **-** | 0.044 | 24.794 | 0.7 | 0.007 |
| **PM10** | **-** | - | - | - | 0.228 |
| **PM2.5** | **-** | - | - | - | 1 |
| **Sox** | **-** | - | - | 1 | - |
| **$CH_4$** | 25 | - | 0.014 | - | - |
| **$N_2O$** | 298 | - | - | - | - |
| **$CO_2$** | 1 | - | - | - | - |
| **SO2** | **-** | - | - | 1 | 0.061 |
| **Normalization Factors**4 | | | | | |
| | **kg $CO_2$-eq/yr** | **kg N-eq/yr** | **kg $NO_x$-eq/yr** | **kg H+eq/yr** | **HHCR kg milli-DALYS/kg** |
| **US Per Capita Emissions** | 24000 | 22 | 1400 | 91 | 24 |
| **Emissions from a Passenger Car** | 4416.825 | 0.368041 | 256.869 | 5.8169 | 0.1624 |

3 Characterization factors were taken from US EPA's LCIA model called TRACI

4 Normalization factors were taken from TRACI for US Per Capita Emissions and Passenger car equivalents were calculated from

"-" not applicable

Even though normalization step in LCIA have benefits, the normalization process have some setbacks. Currently, the key problem in normalization process is the selection of reference system. The selected reference system should be in harmony with the goal and scope of any study. In this study, the characterized data in Table D.3 was normalized using two reference systems: 1) US per capita normalized factors (Ryberg et al. 2013), and 2) Passenger car normalized factors ("Greenhouse Gas Emissions from a Typical Passenger Vehicle" 2015) . The normalized data that uses normalized factors of Table D.2 is shown in Figure D.3.

**Table D.3 Characterized Impact Categories for Alternative Designs**

| Impact Categories | Design 1 | Design 2 (PFC) | Design 3 | Design 4 (PCC) |
|---|---|---|---|---|
| GWP $CO_2$ e (tons) | 52362.32 | 50698.79 | 49505.57 | 21782.36 |
| EUT N-Eq (tons) | 0.36 | 0.25 | 0.25 | 0.12 |
| SMOG (Nox) tons | 89.69 | 63.36 | 62.42 | 30.42 |
| ACID (H+) tons | 3675.99 | 2534.05 | 2511.80 | 2180.83 |
| HHCR milli-DALYS (tons) | 0.95 | 0.74 | 0.69 | 0.62 |

One can observe the difference in impact categories when normalized using different reference systems. For brevity, let us consider the GWP and HHCR impact categories of designs. The GWP (1,982 people equivalent) is the most impacting category when normalized with respective to US per capita emissions where as HHCR (160 people equivalent) has minimal impact. On the other hand, normalization with respective passenger car emissions per year yielded completely different results. The GWP of pavements is equivalent to 10,772 cars whereas HHCR of pavements is equivalent to 23,584 cars. The HHCR of pavements as car equivalent is higher due to the fact the HHCR of a single car is very low, and dividing the HHCR of pavement with a low value resulted in 23,584 cars. Hence, it is evident that the normalized results will be helpful in differentiating the alternatives across the same impact category, however, it cannot be used to compare various impact categories.

One can perceive the importance of selecting the reference system and possibility of misleading, if normalized data is used to compare impact categories. Considering the subjectivity

involved in selection of reference system, there is a need to develop sector specific reference system. A specific reference system exclusively for pavements is not available currently, which leads to use of the existing reference systems.

The alternate way to alleviate the problem of reference system is to use internal normalization, i.e., comparing one design with the other. Internal normalization does not require any reference system. A simple normalization technique is used in this study to explain the internal normalization process. The characterized data in Table D.3 is normalized by dividing the each design impact category results with the maximum among the group of alternate designs as shown in

Table D.4. Each design has an impact category score from 0 to 1. For example, D1 has GWP score of 1 and D4 has 0.42, which implies that D4 emitted only 42 percent of GWP compared with D1.

The advantages of internal normalization are, no need for external normalization factors and can be helpful in normalizing the data that is not well defined. Internal normalization is good at comparing designs across an independent impact category but fails to portray the actual impact on environment. Hence, it is evident that both normalization techniques have their own merits and limitations. Considering the drawbacks of internal and external normalization methods, it is proposed to use the combination of both methods in decision-making. External normalization will help in understanding the significance of the characterized results and internal normalization will aid in comparing the alternatives.

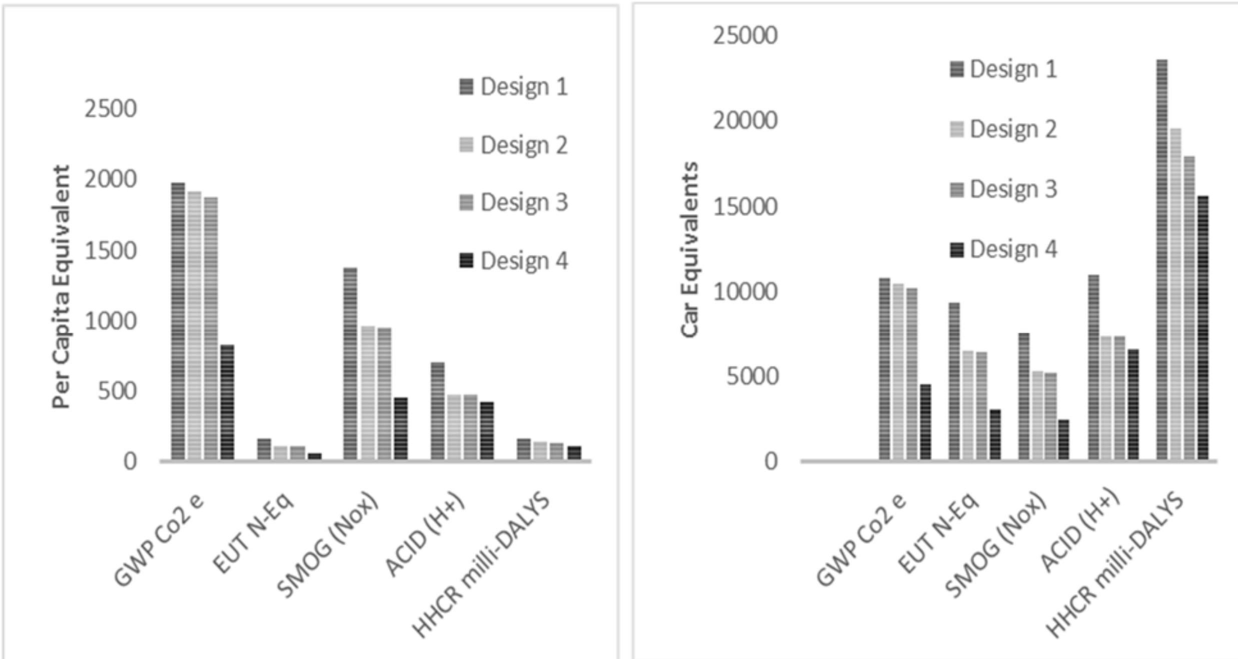



**Figure D.3 Normalized Data for US/ Capita emissions in 2008 and for Car Emissions**

**Table D.4 Internal Normalization Results**

| Impact Category | Design 1 | Design 2 | Design 3 | Design 4 |
|---|---|---|---|---|
| GWP | 1.00 | 0.97 | 0.94 | 0.42 |
| EUT | 1.00 | 0.70 | 0.69 | 0.32 |
| SMOG | 1.00 | 0.70 | 0.69 | 0.33 |
| ACID | 1.00 | 0.67 | 0.67 | 0.60 |
| HHCR | 1.00 | 0.83 | 0.76 | 0.66 |

#### D.4.3.2. Weighting

The reason for employing weighting is to simplify LCIA output. Weighting in LCIA aspires at rating different impact categories against each other to determine their significance with respect to the context of conducting LCA (Stranddorf et al. 2003). As LCA involves numerous impact categories and each impact categories differs from other in their characteristics, Multi Criteria Decision Analysis (MCDA) is one of the useful tools in assigning the weightages. Gloria et al. Gloria et al.(2007) calculated the weightages of various impact categories by employing

Analytic Hierarchy Process (AHP) which is an MCDA method. They obtained input from users, producers, and LCA experts over the weightage of various impact categories. The weightages proposed by Gloria et al. were used in this study.

The weightages created were specifically in the context of assisting environmentally preferable purchasing of building products in the United States (Gloria et al. 2007). Although applying the same weightages for selection of pavements may be inappropriate, the same weightages were chosen in this study to demonstrate the relation between weighting and normalization. Authors encourage developing the weightages for impact categories for each study independently.

All impact categories were normalized to both per capita equivalents and passenger car equivalents. Since, all impact categories have similar unit, an overall environmental impact score can be evaluated by linear weighted aggregation of normalized data. For example, impact score of Design 1 ($IS_1$) shown below is 1,146 residents' equivalent. In other words, the impacts for D1 for one mile is equivalent to impacts on 1146 US residents in 2008. The impact scores (people equivalents) for all designs were [$IS_1$, $IS_2$, $IS_3$, $IS_4$] = [1146, 1062, 1035, 489]. By employing the similar approach the impact scores (car equivalents) for all designs were [$IS_1$, $IS_2$, $IS_3$, $IS_4$] = [16497, 14121, 13341, 9164].

$$IS_1 = (1982\times0.475) + (155\times0.098) + (1378\times0.066) + (698\times0.049) + (160\times0.148) = 1146$$

The process is straightforward if all emissions are characterized into impact categories and then all impact categories are normalized by the same reference system. However, due to discrepancies between various LCA databases, characterization and normalization might not be possible for all emissions. The weightages calculated on internal normalized results were shown in the last four columns of Table D.5. The final weightages of four designs were 0.32, 0.28, 0.27 and 0.14, respectively. Since higher weightages indicates higher environmental impacts, the D4 has less environmental impacts compared to other designs.

## D.5. Conclusions and Discussions

Normalization helps to understand the impacts in a better way. For example, if we compare the impacts presented in Table D.3 (only characterized impacts) and Table D.5 (Normalization of characterized impacts), it is evident that normalization helps in comprehending the impacts clearly. The other advantage of normalization is it makes conveying the results to non-technical stakeholders easily.

Selection of reference system plays a key role in normalization. The purpose of normalization is communicating the environmental impacts to decision makers. The selection of reference system should help decision makers to empathize the impacts. In this study, passenger car equivalent is chosen as a reference system because of multitude reasons. More specifically, the data is reliable, the data helps to normalize the impact categories chosen in this study, a passenger car is a more common unit for various applications in transportation sector, and helps in amplifying the differences in designs. External normalization helps in understanding the impacts due to pavements on a macro level and in differentiating the designs. Internal normalization helps in comparing alternate designs and needs no reference system. Impacts were normalized using US per capita impacts in 2008 and passenger car equivalents. Hence, multiple reference systems can be used in normalization to communicate the magnitude of impacts to decision makers.

The authors of this study propose to use a combination of internal and external normalization, where complete characterization and normalization of impacts is not possible. External normalization aids to comprehend the magnitude of various impacts and internal normalization to compare alternatives. The purpose of performing LCA differs from study to study, hence forming case specific weightages is recommended. We recommend use of multi criteria decision analysis in the estimation of weightages for each impact category by involving key stakeholders. The weighting in LCIA using multi-criteria decision analysis is a potential area for future research.

## Table D.5 Final Weightage Calculations

| **Impact Categories** | **Weightages** | **Normalization System Reference** | | | | | | | | | | | | **Weightages (Internal Normalized impacts)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Per Capita Equivalent | | | | Passenger Car Equivalent | | | | Internal Normalization | | | | | | | |
| | | D1 | D2 | D3 | D4 | D1 | D2 | D3 | D4 | D1 | D2 | D3 | D4 | D1 | D2 | D3 | D4 |
| **GWP** | 0.56 | 1982 | 1918 | 1873 | 824 | 10772 | 10424 | 10179 | 4480 | 1.00 | 0.97 | 0.94 | 0.42 | 0.56 | 0.54 | 0.53 | 0.24 |
| **EUT** | 0.12 | 155 | 108 | 107 | 50 | 9272 | 6453 | 6393 | 3008 | 1.00 | 0.7 | 0.69 | 0.32 | 0.12 | 0.08 | 0.08 | 0.04 |
| **SMOG** | 0.08 | 1378 | 962 | 952 | 451 | 7513 | 5243 | 5189 | 2459 | 1.00 | 0.7 | 0.69 | 0.33 | 0.08 | 0.06 | 0.06 | 0.03 |
| **ACID** | 0.06 | 698 | 471 | 470 | 417 | 10926 | 7371 | 7353 | 6519 | 1.00 | 0.67 | 0.67 | 0.6 | 0.06 | 0.04 | 0.04 | 0.04 |
| **HHCR** | 0.18 | 160 | 132 | 121 | 106 | 23584 | 19560 | 17929 | 15643 | 1.00 | 0.83 | 0.76 | 0.66 | 0.18 | 0.15 | 0.14 | 0.12 |
| | | D1 –Design 1 | | | | D3- Design 3 | | Sum of Weightages | | | | | | 1.00 | 0.87 | 0.84 | 0.45 |
| | | D2 – Design 2 | | | | D4- Design 4 | | Final Weightages (normalizing the sum of weightages) | | | | | | 0.32 | 0.28 | 0.27 | 0.14 |

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# Appendix E

The material of this appendix, is a technical paper entitled “Enhancing Pavement Design Selection by Incorporating Normalization into Life Cycle Impact Assessments” , was selected for publication the International Conference on Transportation and Development (ASCE ICTD) 2016 to be held in Houston, Texas, on 26-30th June 2016.

# Appendix.E. Enhancing Pavement Design Selection by Incorporating Normalization into Life Cycle Impact Assessments

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## E.1. Abstract

To evaluate environmental impacts of pavement, Life cycle assessment (LCA) approach has been proposed by the Federal Highway Administration. Life Cycle Impact Assessment (LCIA) is a vital step within LCA that transforms various emissions into meaningful environmental and human impacts. The LCIA is a four step process: classification, characterization, normalization, and weighting. Due to subjectivity associated with normalization and weighting, International Organization for Standardization proposed to use only first two steps in LCIA. However, normalization helps decision maker(s) in interpreting the environmental impacts of pavements by comparing them to common reference that are understandable and recognizable and ignoring them can lead to biasness in decision-making. Therefore, the focus of this study is to propose a normalization method that minimizes subjectivity associated with currently available methods. A normalization method that combines fuzzy preference relations and Analytic hierarchy process (AHP) was evaluated and the evaluation results are reported in this paper. Although evaluation results are promising, more research work is needed before it can be implemented.

*Keywords*

Life cycle impact assessment (LCIA), Analytic Hierarchy Process, Fuzzy Preference Relations, Normalization.

## E.2. Introduction

Highways significantly impact economy and society which they serve. Additionally, the environment is impacted due to burning of fossil fuels (during construction as well as use phase). Construction and maintenance of highways requires significant amount of natural resources, capital, and workforce. The main factor governing designing pavement structure design is the initial cost of construction. However, the life cycle cost of a specific pavement structure design may be significantly different due to maintenance and rehabilitation requirement. To minimize the impacts on the environment and economy, various feasible pavement structure designs need to be developed and evaluated thoroughly from design to replacement during planning as well as design phase. The environmental impact, during the life of pavement, needs to be assessed through Life Cycle Assessment (LCA) over the design life (Santero et al., 2011). LCA comprehensively quantifies the emissions and energy flows of a product (pavement) in its Life Cycle. International organization of standardization (ISO) released two standards ISO-14040 2006 and ISO-14044 2006 to standardize the LCA methodology and to ensure consistency in performing LCA. Similar to ISO standards, detailed procedure for conducting of LCA has been proposed by United States Environment Protection Agency (US EPA) document (SAIC) 2006. Even though LCA has been proposed by the agencies, they do not specifically provide guidance for performing LCA of pavements (U.S. DOT, FHWA 2014). However, all the guidelines and published literature are in agreement about various stages of conducting an LCA. In general, three basic phases are considered in conducting an LCA and are interpreted throughout the LCA process and the phases are modified accordingly.

**Phase 1 Goal and Scope:** In the first phase, the goal and the scope (boundaries) for conducting LCA are defined (e.g. selection of a pavement design).

**Phase 2 Inventory Analysis:** In this phase various pollutants emitted and energy usage due to a pavement in its life time are estimated. Various databases are available for estimating environmental impacts. Since databases have not been specifically developed for LCA of pavements, more than one database needs to be used.

**Phase 3 Impact Assessment:** The ISO 14044 (2006) defines LCIA as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product (i.e. pavement) system". In LCIA, influence of various pollutants (inventory data) on environment can be demonstrated by converting them into impact categories. For instance, Global Warming Potential (GWP) represents a particular environmental concern of climate change. Impact category amounts can be used to compare alternative designs (Weiland and Muench 2010). LCIA comprises of four components: classification, characterization, normalization, and weighting. Each of the components are discussed in details in the LCIA section. Classification and characterization steps are prescribed for use in LCIA while normalization and weighting are optional due to subjectivity associated with them. Although proposed, most of the previous LCA pavement case studies remained in the stage of performing inventory analysis (Classification) and few characterized the inventory into impact categories (Characterization).

It is essential for decision makers (DMs) to understand the true meaning of the magnitude of each impact category to make a right decision. For example, product A and B produces a GWP of 18,000 and 18,500 tons of CO2e, respectively. Although data suggests that product A is environmental friendly in comparison to product B. However, it doesn't inform DM whether difference of 500 tons of CO2e significantly influences the environment or it is within the specified threshold. The magnitudes of impact categories may be better interpreted by comparing them with an understandable environment context (Sleeswijk et al. 2008). The normalization step aims at addressing this issue and is focus of this study. Similarly, weightings are assigned to various impact categories and there is no standard weighting procedure.

### E.3. Normalization

Normalization aims at converting various impact categories into a common unit by relating them with a standard reference system to facilitate comparisons among alternatives (Lindeijer 1996). The advantages of normalization are: a) it facilitates DMs in understanding the

characterized impacts data, b) it allows to compare different impact categories (Norris 2001) , and, c) it expresses the relative magnitude of the impact scores on a scale which is common to all the categories of impact (Hauschild et al. 2003). Normalization is considered as an optional step due to high risk of subjectivity and the key issues are:

- Selection of a reference system. The quality and completeness of the external data, as national inventories are a combination of various industry reports that vary spatially and temporally (Rogers and Seager 2009).
- Normalization is the risk of over or underemphasizing important criteria based on the reference system (Seppälä and Hämäläinen 2001). For example, if the external reference area has a very little eutrophication, normalized eutrophication may be over emphasized and the final decisions may be masked.
- One more key problem is the associativity of normalized data with weightage. If the weightages for various impact categories are pre-defined, the normalized values are multiplied by the corresponding weights, and these weighted values are added together to form an overall score. However, available reference systems are based on physical midpoint parameters (kg-equivalents) rather than specific end point damages (e.g. mortality), hence, normalized values of are still qualitatively different and not directly comparable.

### E.4. Objectives and Approach

This study has the following two objectives:

- Examine various normalization methods and evaluate the merits and demerits.
- Propose a normalization method with minimal drawbacks of existing method(s).

The normalization methods examined (through a case study) in the study are namely:

I. External normalization

II. Internal normalization by comparing with the best alternative within the group,

III. Outranking internal normalization using PROMETHEE.

“Fuzzy Preference Relations- Analytic Hierarchy Process (AHP)” a method for normalization and weighting is proposed in this study. The various methods were demonstrated through a case study (pavement design selection). The main purpose of this study is to illustrate various methods of normalization rather than providing definitive selection of the most preferable pavement structure design.

## E.5. Case Study

Four equivalent pavement designs were developed for 30 years as shown in Figure E.1 Alternative Pavement Designs. Each of the design consisted of six-lane highway (three lanes on each side) to carry 30 million equivalent single axle load (ESAL) and subgrade conditions were considered to be the same for all designs. The design was performed as per the Texas Department of Transportation pavement design guide (Russel Lenz.W 2011).

### E.5.1. Inventory Analysis

A process approach (LCA) was employed to account for various emissions in pavement designed life. In this study, various inventory models were selected based on the reliability of emission data and feasibility to employ in pavement LCA.

The GREET life cycle model was employed to estimate the emissions from the material extraction and manufacturing and the transportation phase. A hauling distances of all materials (cement, asphalt, aggregates, diesel etc.) as 50 miles to the plants and 12 miles from plants to construction site were assumed. The traffic delay emissions during maintenance operations were estimated using MOVES 2014.

It was assumed that maintenance happens from 9AM—5PM and one lane each side of pavement was closed. Emissions due to traffic delays during initial construction and emergency maintenances were not considered in this study. Construction equipment emissions during operation were drawn from the EPA’s NONROAD model which was embedded in the MOVES 2014 (US 2014). The type of equipment and working hours of equipment were estimated based on the RSMeans data 2012.

The inventory data (1 mile pavement) of various pollutants (which were commonly produced by the LCI models) and energy consumption for the four pavements are shown in the Table E.1(Life Cycle Inventory).The energy consumption calculated using the GREET has capability of providing the division of various fuels that caused the energy consumption, whereas the other models (MOVES, NONROAD) provides only the energy consumption not the classification. Hence, energy consumption was not characterized into fossil fuel depletion (impact category).

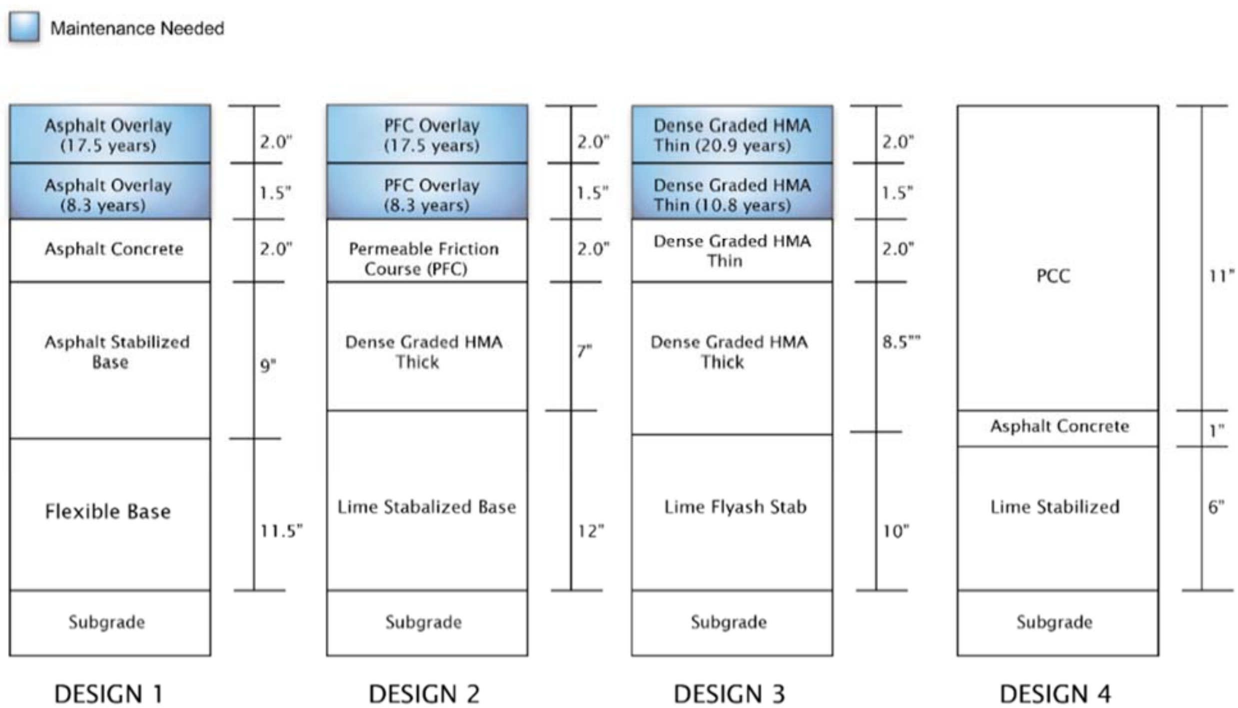


**Figure E.1 Alternative Pavement Designs**

### E.5.2. Life Cycle Impact Assessment (LCIA)

#### E.5.2.1. Classification

In this inventory step, pollutants are assigned to relevant impact categories like carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$) etc. contribute to GWP impact category. Similarly, the other pollutants are classified into groups based on the impact category. Table E.1

displays the classification of various impact categories namely: GWP, Eutrophication (EUT), Smog (SMOG), Acidification (ACID), and Human Health Criteria Air Pollutants (HHCR).

#### E.5.2.2. Characterization

In characterization, various pollutants are converted to a common impact category and the factors required to transform the emissions are called characterization factors (Table E.1). These conversion factors were provided by the EPA's impact assessment Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) which strives in attaining consistency in environmental decision-making. Table E.1 shows the characterized data of selected impact categories.

#### E.5.2.3. Normalization

It is evident that each impact category have different units. They can be understood by normalizing them with a reference value (Sleeswijk et al. 2008).

##### *E.5.2.3.1. External Normalization*

In this method, the characterized data is compared to the standard reference systems (e.g. US per capita emission factors). The characterized data in Table E.1 is normalized using the factors proposed by Ryberg et.al (2013) which are U.S. per capita emissions in 2008. Figure E.2 shows the normalized data of various impact categories into equivalent to number of people impacted during 2008 in U.S. Energy consumption is not normalized due to lack of a comparison factor.

##### *E.5.2.3.2. Internal Normalization*

This method alleviates the need of reference system and helps to include all impact categories (e.g., energy consumption in this case study). Two types of internal normalization are discussed in this study. The first one is performed by comparing alternatives with the best alternative for each impact category as exemplified in ISO TR 14047 (2003). Figure E.3.a shows the normalized results with respect the best design and results indicate how many times the impact of each alternative compared with the best. The best alternative has value +1 and the remaining

alternatives are expressed in negative. It is the easiest way of normalizing and gives an instant information to DMs. These type of normalizations do not consider the significance of the difference between alternatives for any impact category. For example the EUT value for Design 1 is 0.36 and Design 4 is 0.12. It shows that the Design 1 has three times more EUT than Design 4, but difference is not well examined.

**Table E.1 LCI of Four Pavement Designs per Mile Length, Characterization**

| a) Life Cycle Inventory | | | | | |
|---|---|---|---|---|---|
| **Pollutant** | **Design 1** | **Design 2** | **Design 3** | **Design 4** | |
| Volatile Organic Compounds (VOC) in tons | 4.5E+00 | 4.0E+00 | 3.6E+00 | 3.1E+00 | |
| Carbon Monoxide (CO) in tons | 8.7E+01 | 8.1E+01 | 7.6E+01 | 3.3E+01 | |
| Nitrogen Oxides ($NO_x$) in tons | 8.5E+01 | 5.9E+01 | 5.9E+01 | 2.8E+01 | |
| Particle Matter (PM10) in tons | 5.9E+00 | 4.0E+00 | 3.9E+00 | 4.0E+00 | |
| Particle Matter (PM 2.5) in tons | 1.9E+00 | 2.0E+00 | 1.7E+00 | 1.6E+00 | |
| Sulfur Oxides ($SO_x$) in tons | 5.4E+00 | 3.3E+00 | 3.3E+00 | 2.1E+01 | |
| Methane (CH4) in tons | 2.2E+01 | 1.5E+01 | 1.4E+01 | 7.6E+00 | |
| Nitrous Oxide ($N_2O$) in tons | 5.1E-01 | 4.3E-01 | 3.7E-01 | 2.5E-01 | |
| Carbon Dioxide $CO_2$ in tons | 5.2E+04 | 5.0E+04 | 4.9E+04 | 2.2E+04 | |
| Sulfur Dioxide ($SO_2$) in tons | 5.2E+00 | 2.6E+00 | 2.9E+00 | 1.3E+00 | |
| **Energy Consumption in million British thermal units (mmbtu)** | **1.7E+11** | **1.1E+11** | **1.0E+11** | **2.8E+11** | |
| b) Classification and Characterization factors (US EPA LCIA Model TRACI) | | | | | |
| **Pollutant** | **GWP kg CO2-eq/kg** | **EUT kg N-eq/kg** | **SMOG kg Nox-eq/kg** | **ACID kg H+eg/kg** | **HHCR kg milli-DALYS/kg** |
| VOC | - | - | 3.595 | - | |
| CO | - | - | 0.055 | - | 0.0003 |
| Nox | - | 0.044 | 24.794 | 0.7 | 0.007 |
| PM10 | - | - | - | - | 0.228 |
| PM2.5 | - | - | - | - | 1 |
| Sox | - | - | - | 1 | - |
| $CH_4$ | 25 | - | 0.014 | - | - |
| $N_2O$ | 298 | - | - | - | - |
| $CO_2$ | 1 | - | - | - | - |
| SO2 | - | - | - | 1 | 0.061 |
| c) Characterized Data | | | | | |
| **Impact Categories** | **Design 1** | **Design 2** | **Design 3** | **Design 4** | |
| GWP $CO_2$ e (tons) | 52362.32 | 50698.79 | 49505.57 | 21782.36 | |
| EUT N-Eq (tons) | 0.36 | 0.25 | 0.25 | 0.12 | |
| SMOG (Nox) tons | 89.69 | 63.36 | 62.42 | 30.42 | |
| ACID (H+) tons | 3675.99 | 2534.05 | 2511.80 | 2180.83 | |
| HHCR milli-DALYS (tons) | 0.95 | 0.74 | 0.69 | 0.62 | |
| Energy Consumption(mmbtu) (not characterized) | 1.71E+11 | 1.08E+11 | 1.02E+11 | 2.81E+11 | |

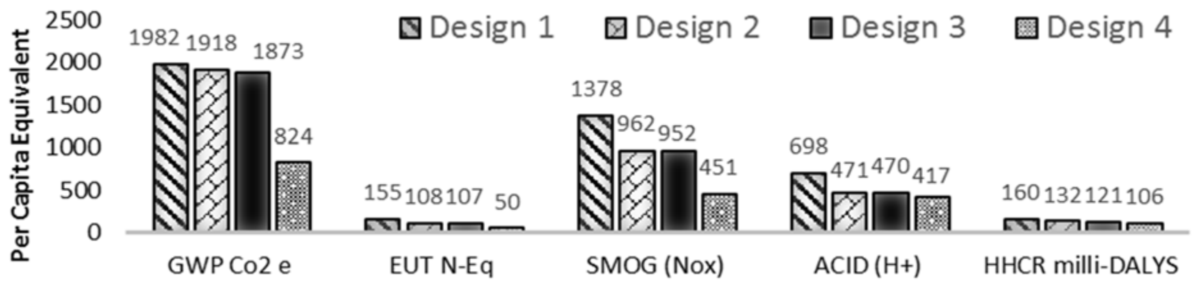


**Figure E.2 External Normalization Using TRACI Normalized Factors**

#### *E.5.2.3.3. Outranking Internal Normalization*

The stepwise procedure for PROMETHEE was explained by Taillandier and Stinckwich (2011). It is also an internal normalization technique which assigns ranking of designs based on the significance of the difference between impact values among designs. Figure E.4 shows a typical preference function $P_k(a_i, a_j)$ giving the degree of preference of design $a_i$ over design $a_j$ for a given criteria $f_k$. Preference function $P_k(a_i, a_j)$ is a function of difference $d = f_k(a_i) - f_k(a_j)$. The preference index for the preference relation can be obtained by using the following relation (equation 1). There are other types of preference criteria like Gaussian, Quasi, Linear Preference etc.

$$P_k(a_i, a_j) = \begin{cases} 0, \text{if } d \leq q_k \\ \frac{d - q_k}{p_k - q_k}, \text{if } q_k \leq d \leq p_k \\ 1, \quad \text{if } d \geq p_k \end{cases} \qquad (1)$$

Indifference threshold $(q_k)$ is the limit where the difference between alternatives is insignificant and preference threshold $(p_k)$ is the limit where the difference between alternatives is very significant. Both these limits are used to determine the level of preference between two designs. For demonstrative purposes, preference threshold of each impact category equal to the 1.5 times the standard deviation of the characterized inventory data in that category and indifference threshold limit is half of the preference threshold. Figure E.3 b shows outranking normalized values of designs for various impact categories. The positive outranking flow indicates

to what extent each design outranks all the others. The negative outranking flow expresses to what extend each design is outranked by others. The higher the value the better the design will be.

External normalization helps in understanding the characterized data in a global perspective, and has drawbacks like selection of reference system, chances of biasing the end results towards an impact category (explained in weighting section), and ignoring some uncharacterized impacts (e.g., energy consumption in this study). Internal normalization alleviates the need of a reference system, considers uncharacterized data, but the focus of the method is more on numerals than impacts. Outranking normalization considers the significance of difference between the alternatives impact values, but it is often challenging to assign threshold (indifference and Preference) for each impact category. In both methods, the characterized data is normalized based on a pseudo criteria that may not be represent the DM's judgement.

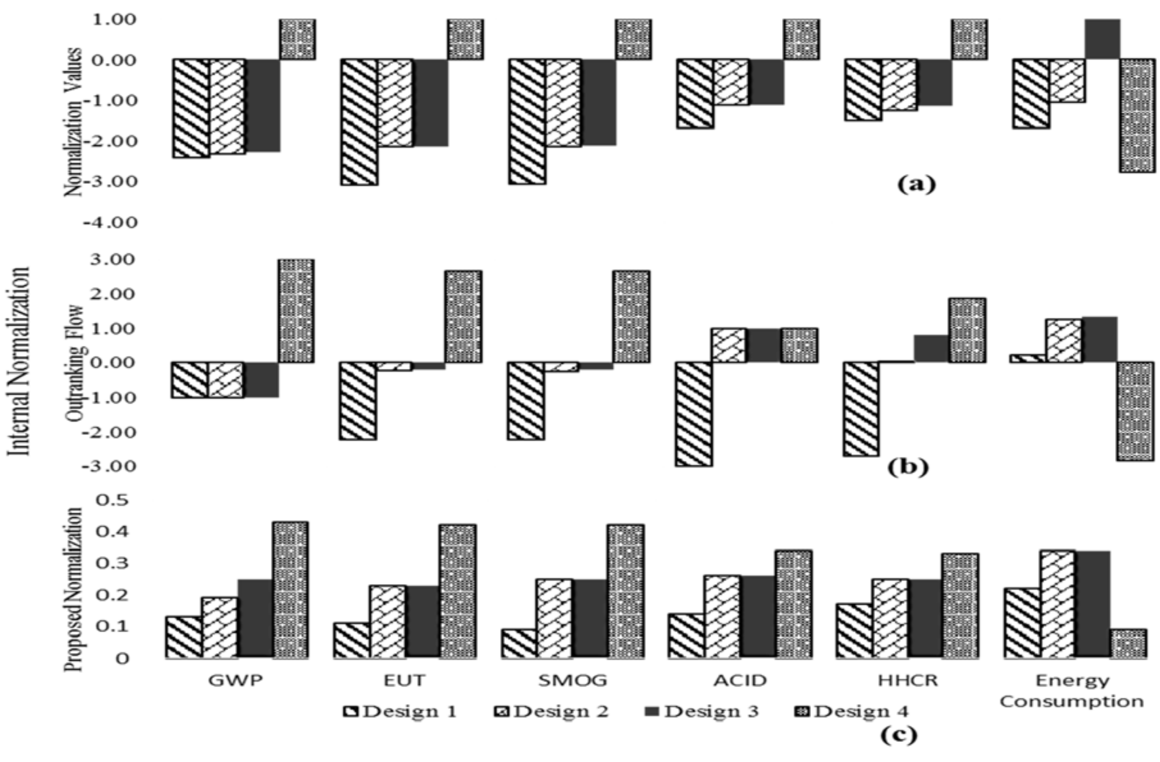


**Figure E.3 (a) Internal Normalization with respect to the Best Design (b) Internal Normalization Using Outranking Normalization (c) Internal Normalization Using Proposed Method**

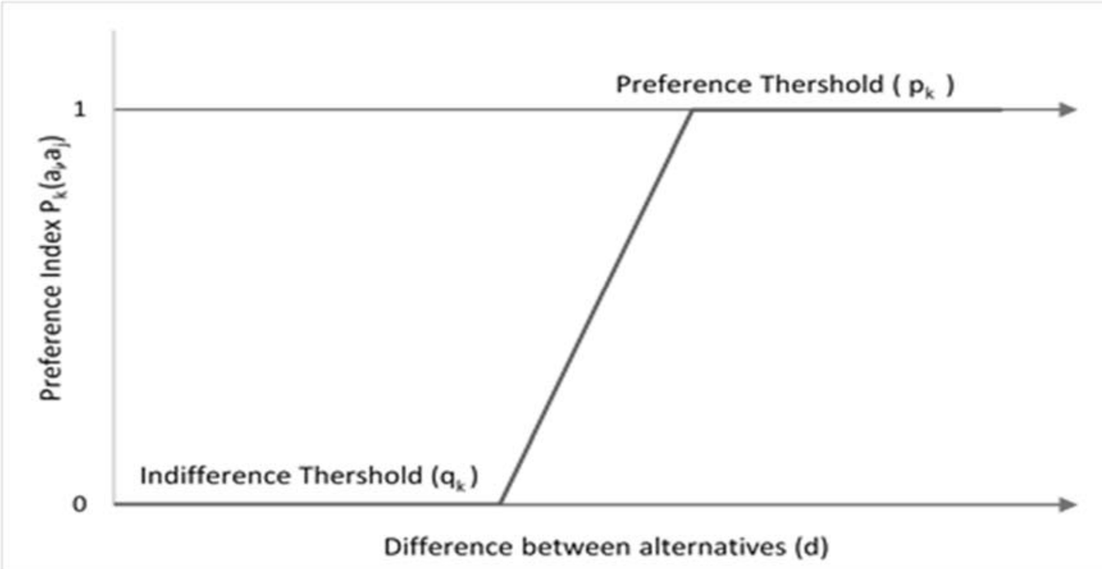


**Figure E.4 Preference Criteria**

In this study we propose to use Fuzzy Preference Analytic Hierarchy Process (AHP) for normalization of characterized data. Proposed method alleviates the problem of non-sensitivity (external normalization) of normalized results to weightages. The characterized data is normalized based on the decision maker choices. Even, the uncharacterized data can also be normalized. This method permits decision makers to use multiple reference system in external normalization. The normalization is performed through the intervention of DMs rather than pseudo criteria.

## E.6. Proposed Method for Normalization

The study proposed an internal normalization method, but the authors recommend to perform external normalization initially and to use that results as a guidance for internal normalization. Sometimes DMs needs to use multiple reference systems to understand the significance between two designs for an impact category. For example, external normalized EUT values for Design 1 (0.36 N-Eq tons) and Design 2 (0.25 N-Eq tons) as per Figure E.2 are 155 and 108 people equivalent. The difference between Design 1 and Design 2 is 47 people equivalent, which appears as not a significant difference. If the same impacts are normalized with respect to emissions of an average passenger car in US, then the normalized values are 9272 and 6452

(difference is 2820 car equivalents) passenger cars equivalent for Design 1 & 2 respectively("Greenhouse Gas Emissions from a Typical Passenger Vehicle" 2015). The proposed method allows to use multiple reference systems for normalizing the data. The theories of proposed method are explained briefly in the following sections.

### E.6.1. Fuzzy Preference Analytic Hierarchy Process (AHP)

AHP is a widely used multi criteria decision model for its simple analytical efforts and ease of understanding. In AHP, the relative significance between alternatives is evaluated (called as pairwise comparison in AHP terminology) based on a predefined significance scale. AHP also has capacity to check the consistency in decision maker pairwise comparisons. Once the required pairwise comparisons were given by DM, AHP uses multiplicative transitivity property to back calculate the remaining pairwise comparisons. Once, pairwise comparisons were complete, simple analytic methods are used to calculate final weightages among alternatives compared.

In spite of its merits, the AHP method has drawbacks. It requires rigorous consistency requirement in pairwise judgments which shifts the focus of DMs towards satisfying consistency rather than his/her actual judgments (Li et al. 2013), and also needs more number of pairwise comparisons (n(n-1)/2 pairwise comparisons for analyzing n criteria) (Lee et al. 2014). In order to alleviate the drawbacks associated with AHP, Herrera-Viedma et al. (2004) proposed to use the additive transitivity property on fuzzy preference relations. This method needs $(n-1)$ pairwise comparisons unlike $n\ (n-1)/2$ inputs required for evaluating $n$ criteria by the conventional AHP. The remaining pairwise comparisons are constructed based on $(n-1)$ inputs by using the additive transitivity property on fuzzy preference relations.

### E.6.2. Herrera Viedma Approach

Consider a set of alternatives, $X = \{x_1, x_2, \dots . x_n\}$ each alternative is related with a reciprocal multiplicative preference relation $A = (a_{ij})$ for $a_{ij} \epsilon [1/q, q]$ (e.g.,(1/9,9)) where $q$ is the range of comparison scale .The value of 9 (q) indicates as most preferred option and 0.11(1/q) as least preferred. For example, the pairwise comparison of $x_1$ to $x_2$ was given as $a_{12} = 9$ (i.e.,

$x_1$ is more preferred than $x_2$) using the multiplicative transitive property ($a_{12} \times a_{21} = 1$) the pairwise comparison $x_2$ to $x_1$ can be calculated as $1/a_{12} = a_{21} = 1/9$ ($x_2$ is least preferred than $x_1$). Instead of using multiplicative transitive property in AHP, fuzzy additive transitive property can be used. According to additive transitive property($a_{12} + a_{21} = 1$), but $a_{12}$ has a value of 9 which yields $a_{21}$ to '-8', which is beyond the comparison scale (1/9, 9). To apply the transitive property, the pairwise comparison needs to be normalized to a scale of 0 to 1 and fuzzy preference relation can be used for converting the pairwise comparisons. The following equation 2 shows the fuzzy preference relation $P = (p_{ij})$ with $p_{ij} \epsilon$ [0,1] associated with A is given as

$$p_{ij} = g(a_{ij}) = \frac{1}{2}(1 + \log_q a_{ij}) \quad (2)$$

This proposition is very important because it can be used to construct a consistent fuzzy preference relation from the set of $n - 1$ values $\{p_{12}, p_{23}, \dots, p_{(n-1)n}\}$. In simple terms, using normal AHP needs n (n-1)/2 pairwise comparisons from DMs and remaining were calculated by using multiplicative transitive property, whereas using transitive additive property needs (n-1) pairwise comparisons from DMs. The pairwise comparisons are converted to fuzzy preference relation, remaining pairwise comparisons are constructed using additive transitive property as shown in Equation 3. Once, all the pairwise comparisons are back calculated, both methods use same analytic process for estimating weightages. If $p_{i,j} = 1$, means alternative i is the most preferred than alternative j, if $p_{i,j} = 0$, i is least preferred than j, $p_{i,j} = 0.5$ both i and j are equivalent.

$$\begin{cases} p_{ij} + p_{jk} + p_{ki} = \frac{3}{2}, \forall\, i, j, k \\ p_{ij} + p_{jk} + p_{ki} = \frac{3}{2}, \forall\, i < j < k \\ p_{i(i+1)} + p_{(i+1)(i+2)} + \dots + p_{(j-1)(j)} + p_{(j)(i)} = \frac{j-i+1}{2}, \forall\, i < j \end{cases} \quad (3)$$

$$f: [-k, 1 + k] \to [0,1], f(x) = \frac{x + k}{1 + 2k} \quad (4)$$

Sometimes the constructed preference relation falls in the interval $[-k, 1+k], k > 0$ rather than $[0, 1]$. Then, the obtained values can be transformed within the desired range $[0, 1]$ using a transformation function that preserves reciprocity and additive consistency. The transforming function shown in Equation 4 can be used to preserve consistency. To demonstrate the method, Ryberg et al. (2013) normalization method was selected for impact categories GWP, EUT, SMOG, ACID, HHCR, and energy consumption were normalized by comparing it with US Transportation Sector Energy Consumption for 2014 ("Annual Energy Review " 2015).

The normalized values are shown in the Figure E.2 can be used as a guide for DM's for pairwise comparisons. An example of proposed method is demonstrated (Figure E.5) for energy consumption of various designs. The designs were compared based on the external normalized data and the pairwise comparisons required by proposed AHP were assigned (by a DM) as shown in Step 1 of Figure E.5. In this study, the scale used for pairwise comparisons (1/9 to 9) is similar to scale proposed by Saaty (1980). For example the Design 3 vs Design 4 has a pairwise comparison of 9, which indicates that the Design 3 has very low energy consumption than Design 4 i.e., Design 3 is preferred than Design 4. Once the pairwise comparisons matrix is filled as shown in step 4, the final normalized values for energy consumption are calculated using computations of AHP method. The normalized weights obtained in this example were $\{0.22, 0.34, 0.34, 0.09\}$ respectively. Similarly, the normalization factors are calculated for other impact categories and are displayed in Figure E.3c. There is an association between weighting and normalization methods as explained below.

**Table E.2 Normalized Data**

| **Designs** | **Normalization** | | | | | |
|---|---|---|---|---|---|---|
| | **No of equivalent people in US impacted in 2008** | | | | | **% Transportation sector energy consumption for 2014** |
| | **GWP** | **EUT** | **SMOG** | **ACID** | **HHCR** | **Energy Consumption** |
| Design 1 | 1982 | 155 | 1378 | 698 | 160 | 0.34 |
| Design 2 | 1918 | 108 | 962 | 471 | 132 | 0.21 |
| Design 3 | 1873 | 107 | 952 | 470 | 121 | 0.20 |
| Design 4 | 824 | 50 | 451 | 417 | 106 | 0.55 |

Step 1: Pairwise comparisons from DMs

| | Design 1 | Design 2 | Design 3 | Design 4 |
|---|---|---|---|---|
| Design 1 | 1 | 1/3 | | |
| Design 2 | | 1 | 1 | |
| Design 3 | | | 1 | 9 |
| Design 4 | | | | 1 |

Step 2: Conversion of Pairwise comparisons into Preference Relations

| | Design 1 | Design 2 | Design 3 | Design 4 |
|---|---|---|---|---|
| Design 1 | 0.5 | 0.25 | | |
| Design 2 | | 0.5 | 0.5 | |
| Design 3 | | | 0.5 | 1 |
| Design 4 | | | | 0.5 |

Step 3: Decision Matrix Conversion (Equation 2)

| | Design 1 | Design 2 | Design 3 | Design 4 |
|---|---|---|---|---|
| Design 1 | 0.5 | 0.25 | 0.25 | 0.75 |
| Design 2 | 0.75 | 0.5 | 0.5 | 1 |
| Design 3 | 0.75 | 0.5 | 0.5 | 1 |
| Design 4 | 0.25 | 0 | 0 | 0.5 |

Step 4: Perform Check and Transform using Equation 4, if needed

| | Design 1 | Design 2 | Design 3 | Design 4 |
|---|---|---|---|---|
| Design 1 | 0.5 | 0.25 | 0.25 | 0.75 |
| Design 2 | 0.75 | 0.5 | 0.5 | 1 |
| Design 3 | 0.75 | 0.5 | 0.5 | 1 |
| Design 4 | 0.25 | 0 | 0 | 0.5 |

**Figure E.5 Normalized Values for Energy Consumption Estimation.**

### E.7. Weighting

Weighting in LCIA aspires at rating different impact categories against each other to determine their significance with respect to the context of conducting LCA (Stranddorf et al., 2003). One such attempt was reported in 2007 by Gloria et al. They calculated the weighting of various impact categories by obtaining input from users, producers, and LCA experts over the weightage of various impact categories. The weightages created were specifically in the context of assisting environmentally preferable purchasing of building products in the U.S. In this study the authors assumed similar weightages only to demonstrate the relationship between normalization and weighting. The weightages for GWP, EUT, SMOG, ACID, HHCR, and Energy consumption are 47.5%, 9.8%, 6.6%, 4.9%, 14.8%, and 16.4% respectively. Since the normalized data (external) has similar units, the linear weightage of the four designs (Σ normalized data X weightages) yielded the following results as shown in Table E.3 .

In external normalization scenario, the normalized impacts of GWP is in the range of 800-2,000 per capita equivalent and HHCR is 100-160, irrespective of the weightages assigned. The results are biased towards GWP and is less sensitive to change in weightages. If another reference system is selected where normalized HHCR is dominating than other impacts, then the results will

be biased towards HHCR. Hence, linear weighted sum of normalized impacts with the predefined weights may not be practical for external normalization. In addition, design 4 in terms of energy consumption (related with fossil fuel depletion) is not considered for normalization due to inventory data limitations that may affect the final design selection. Internal normalization (compared with best solution) alleviates this problem. In this study the final weightages are in favor of Design 4 irrespective of normalization method, because the Design 4 outperforms other designs in five out of six impact categories. The advantage of proposed method will be more evident if the alternatives more competitive with each other.

**Table E.3 Weightages of Designs from Various Methods**

| Design | External Normalization | | Internal Normalization (compared with best) | | Outranking Normalization (PROMETHEE Method) | | Proposed Normalization (PAHP) | |
|---|---|---|---|---|---|---|---|---|
| | Score | Rank | Score | Rank | Score | Rank | Score | Rank |
| 1 | 1309.44 | 4 | -222.67 | 4 | -1.35 | 4 | 0.15 | 4 |
| 2 | 1216.02 | 3 | -187.04 | 3 | -0.25 | 3 | 0.23 | 3 |
| 3 | 1187.86 | 2 | -148.78 | 2 | -0.12 | 2 | 0.26 | 2 |
| 4 | 547.62 | 1 | 38.35 | 1 | 1.72 | 1 | 0.35 | 1 |

### E.8. Conclusions

The decisions made without normalization may led to improper selection as DM's incline towards their first impressions or depend on their own intuition. Systematic approach is required for selection of any alternative (design), hence, this study proposed a new normalization method using Proposed AHP (PAHP) method. The PAHP alleviates the drawbacks involved in conventional AHP and aids decision makers to normalize the characterized data considering the context of the study. The proposed method can also be applied to weighting phase of LCIA as well.

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# Appendix F

The material of this appendix, is a technical paper entitled “Feasibility of Incorporating Social Life Cycle Assessment in Sustainability Assessment of Highways” , was presented at the 3$^{rd}$ Conference of Transportation Research Group of India (3rd CTRG) , it was assigned a manuscript number “641”.

# Appendix.F. Feasibility of Incorporating Social Life Cycle Assessment in Sustainability Assessment of Highways

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## F.1. Abstract

Selection, design and construction of pavement structures in itself is a complex process and the addition of sustainability in the process increases complexity as it involves multiple criteria like economy, environment, social, etc. The promising approach to addressing sustainability in pavements is through economic, social, and environmental life cycle assessment (LCA). Initially, the social LCA (SLCA) component was disregarded due to the unavailability of inputs and the complexity of evaluating the entire life cycle. With increasing emphasis on social aspects in sustainability, the focus has increased to include SLCA in decision-making process through various tools like corporate social responsibility (CSR), triple bottom line (TBL), social impact assessment (SIA), etc. Even though each one of them is focused on different phases of the project and at different levels of organization, these tools can be used as supplement for social life cycle assessment (SLCA). The objective of this study is to review existing SLCA literature and evaluate feasibility of using proposed tool(s) for SLCA of pavements. To accomplish study objective, 50+ journal articles, reports, dissertations etc., were studied and the advancement achieved in various sectors that can be modified for application in transportation construction sector have been discussed. An approach for inclusion of SLCA in highway construction has been proposed. In line with the proposed methodology, a case study was performed to evaluate social impact on highway construction.

Keywords: Social Life Cycle Assessment (SLCA), Social Impacts, Highway Construction

## F.2. Introduction

To ensure availability of resources for future generations, the current and future infrastructure development needs to use a sustainable approach. Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland et al. 1987). This definition has been criticized severely for its vagueness (McKenzie 2004) and Mihelcic et al. (2003). Mihelic et al. [3] defined it as "Design and operation of human and industrial systems to ensure that humankinds use of natural resources and cycles do not lead to diminished quality of life due to either losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment." Human well-being not only depends on natural resources and capital but also on nourishing neighborhood. The functioning of society can equally be seen as a resource to preserve and/or enhance. Sustainable is founded on environment, economy and social dimensions. Little attention has been devoted to understanding the social impacts, which is different from environmental or economic sustainability. To appreciate social sustainability, understanding the social aspect of sustainability is important and is focus of this study.

## F.3. Objectives

The following are the objectives for the present study: 1) to evaluate the existing concept of social life cycle assessments (SLCA) and 2) to synthesize the advancements achieved in SLCA by other sectors that can be incorporated into construction sector especially to the surface transportation sector.

## F.4. Approach

To identify and evaluate, various SLCA articles were surveyed in key journals. Little research has been published on SLCA and/or social sustainability in the construction sector. Therefore, the search was expanded to include SLCA and social sustainability approach in sectors other than transportation. The expanded search identified publications and were thoroughly studied and sorted out based on the following criteria:

1. The publications pertaining to the field of construction and dealing with social sustainability directly or indirectly.
2. The publications that relate to social life cycle assessments of products.

The publications were clustered into various groups based on geography, sectors (construction or non-construction), nature of article (qualitative or quantitative) and year of publication. Clustering assisted in understanding the evolution of SLCA and Figure F.1 displays the characteristics of the articles selected for this study.

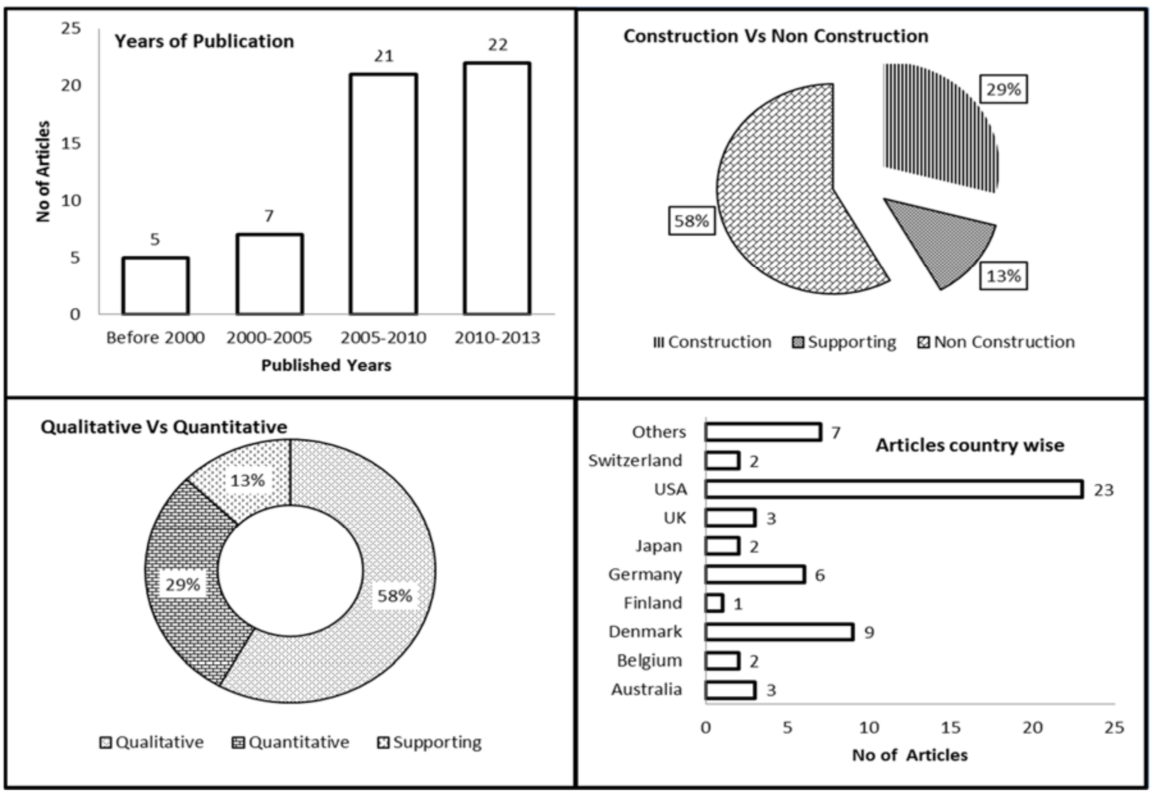


**Figure F.1 Characteristics of Selected Literature**

## F.5. Literature Research

Social sustainability is a global theory i.e., many parties are involved in supply chain of a products life cycle and to attain a sustainable product, commitment of all counterparts is paramount. Since there is no standardized SLCA approach, identification of a methodology for conducting SLCA was specially emphasized while reviewing publications. Definition of

sustainability plays a key role and some definitions are discussed below. A product or process is advantageous compared with alternative product(s) or processes that have the same benefit with regard to the social dimension of sustainability and its positive contribution to attain the social goals established in the international sustainable development debate is greater (or if it's negative contribution is smaller) (Schmidt et al. 2004). Social sustainability occurs when the formal and informal processes; systems; structures and relationships actively support the capacity of current and future generations to create healthy and livable communities. Socially sustainable communities are equitable, diverse, connected and democratic and provide a good quality of life (McKenzie 2004). Why is definition important? It is required for development of outline for measuring results within the context of a study. It also explains the reason for the study as well as condition for the study. Defining sustainability is also the key; does social sustainability means no negative social impacts or reducing social impacts or increasing social benefits.

There are various tools to address social sustainability. Triple bottom line (TBL) reporting is one of them. It is a corporate communication report to stakeholders explaining the company's conduct towards business by managing economic, environmental and social aspects (Group of 100 (Australia) and Birch 2003). It is a more or less another corporate year-end report and social dimensions will always be a secondary dimension compared to economy. Report is influenced by corporate supremacy and abiding to the guidelines of TBL is questionable (Jackson et al. 2011) and (Norman and MacDonald 2004). TBL has drawbacks such as lack of clarity and consensus regarding what comprises of social dimension. Corporate social responsibility (CSR) is another tool growing popular in business communities. CSR is more focused on the enterprise/management level and in some companies it extends up to facility level. CSR also have similar drawbacks as TBL. Social impact assessment (SIA) is more driven towards the impacts at facility or site level. Social life cycle assessments (SLCA) examines management practices, continuously focused on products at facility level where the unit process are located and includes information across product life cycles (UNEP-SETAC Life Cycle Initiative 2009) . Thus, SLCA

is the best currently available tool to address social sustainability, which is further discussed in the following section.

### F.6. Social Life Cycle Assessments (SLCA)

SLCA is a technique that aims to assess the social and socio-economic aspects of product and their potential positive and negative impacts along with their life cycle (UNEP-SETAC Life Cycle Initiative 2009) . It uses the available science to collect the best available data to report on social impacts (positive and negative) in product life cycles from extraction to final disposal. It is a holistic process and helps decision makers in identifying the hotspots in products life cycle and it is helpful in promoting improvement of social conditions in product life cycles, aids decision-making, to set up strategies, action plans, etc. (Benoît et al. 2010) . The major issues with SLCA are that it requires enormous sets of data, there is no established systematic way of addressing it, and the published literature is dispersed. Since it involves vast theoretical concepts and practical challenges (Schmidt et al. 2004), understanding the concept of SLCA and its applicability in addressing the problem needs to be well established.

### F.7. Framework of Social Life Cycle Assessment

Various researchers [(UNEP-SETAC Life Cycle Initiative 2009) , (Benoît et al. 2010) , (Hunkeler 2006a), (Paragahawewa et al.2009), (Bo P Weidema 2006)] have suggested using approach similar to LCA-E. In line with ISO 14040 (2006) and 14044 (2006) , the phases involved in LCA-E are: 1) Goal and scope definition, 2) Inventory analysis, 3) Impact assessment and 4) Interpretation.

#### F.7.1. Goal and Scope Definition

The nucleus of whole assessment lies in this phase as it describes what is desired to protect and promote with SLCA method. As social impacts are numerous, quantifying all impacts throughout the life of a product is not feasible. Scope is defined considering the time, cost, and availability of data pertaining to social impacts, quality of data and association of impacts with

goal of the study. In SLCA methodologies, the term 'Area of protection (AoP)' is used for setting goal (what is of value to human society). "Human health and Well-being" is the AoP suggested by Dreyer et al. (2006) and Weidema (2006) . Schmidt et al. (2004) suggested 'Societal Wealth'. Impact categories that portray AoP should be identified like labor rights, health and safety, community impacts etc. After identifying the social impact categories allied social themes needs be defined, for example impact categories labor rights may have several subcategories like child labor, gender equity, force labor etc. Next step is to identify the social impact indicators that describe the subcategories.

### F.7.2. Inventory Analysis

In this phase, data is collected based on goal and scope definition. Social impact categories are evaluated through a set or single social indicator. Selection of social indicators is dependent on the impacts that are being analyzed. SLCA is conducted to promote improvement in social conditions and in the overall socio- economic performance of a product throughout its life cycle for all of its stakeholders (Jørgensen et al. 2008). To evaluate social conditions, indicators are required to quantify the impacts. According to Weidema (2006), the requirement for a good social indicator is that it permits quantification of the extent (incidence or prevalence) as well as duration and severity of the considered aspect. Selections of social indicators are based on availability of data, quality of available data, and possess a valid impact pathway between indicator and the impact category.

### F.7.3. Impact Assessment

In this phase, inventory data is modelled into impacts. Presently, there is no accepted social impact assessment method. As per ISO 14044 (2006), the impact assessment consists of four steps: classification, characterization, normalization and analysis of data quality. In classification, step inventory results are assigned to relevant impact categories. Characterization is to aggregate inventory data within same impact category 14044 (2006). In SLCA, the characterization models are more complex than LCA-E as many social impacts cannot be aggregated using traditional

quantitative methods (Dreyer et al. 2010). Norris (2006) proposed to use life cycle attribute assessment for impact assessment because attributes of the process are more important than measured quantities per unit of process output. The attributes may be like child labor free processes, fair trade certification, etc.

Dreyer et al. (2010) proposed a multi criteria indicator model for assessing the social impact categories based on a score card and implemented it in six companies (Dreyer et al. 2010b). This indicator evaluates the efforts of a company to mitigate social issues and it delivers a score which represent the company's performance aggregated over the life cycle of the product. Weidema (2006) suggested a characterization indicator Quality Adjusted Life Years (QALYs), which is an accumulation of all impacts towards the reduction of average well-being life. According to Weidema, each social indicator has a severity and duration and by accruing number of occurrences of incidence, their duration and severity, the total impact i.e., reduction in well-being can be estimated. Hunkeler (2006b) used working hours as indicator to estimate social impacts. The salary made through working hours may be spent to improve impact categories like housing, health care, education and necessities. Normalization step is considered optional in impact assessment and it makes sense only with the quantitative results (Grießhammer et al. 2006). The outcomes from social indicators are related to a reference system i.e., in relation to total impacts in a region or company. The final step in impact assessment method is analysis of the data quality, which comprises of validity of data, relevance of data with respect to AoP, measurement methods employed in assessment, and understanding uncertainty issues involved in assessment.

**F.7.4. Interpretation**

In this phase the results are assessed in order to draw conclusions and also provide limitations of the study accompanied with recommendations to decision makers (UNEP-SETAC Life Cycle Initiative 2009).

### F.8. Social Sustainability in Construction

Till now more attention is paid towards products rather than services. Gidado (1996) stated that construction is complex and the sources for complexity are numerous due to uncertainty and interdependence among tasks. Fenandez-solis said construction is not a single industry but an "industry of industries" which requires additional foundational work apart from traditional industrial approaches. For example, the use phase in LCA-S has been typically neglected as most researchers agree that the use phase is difficult to evaluate but in case of highways the impacts on local communities will be more during use phase. Chasey and Agrawal (2012) considered "community development through collaboration" as social theme for construction of semiconductor manufacturing facilities. Strengthening the local technical base, engaging local communities in construction planning and developing construction schedules to reduce traffic delays were considered as social indicators. Gatti et al. (2012) assessed social benefits by monitoring workers physical strain using physiological status monitors (PSM). Workforce safety and well-being was considered as social theme. Three commercially available PSM's (BH,HxM,EQ-01) were compared to monitor the physical strain i.e heart rate, breathing rate, skin temperatures etc., in workers during dynamic activities. Behm (2005) determined that a clear relationship exists between construction fatalities and the construction safety concept design. After reviewing 224 fatality investigation reports, Behm identified 42% of fatalities would have been eliminated if construction safety concepts were designed properly. To validate this finding, further research was conducted by Gambatese et al. (2008) to identify design role in construction accident causality and prevention. An expert panel was established to judge whether fatalities were related to design by evaluating 224 causalities. Behm (2005) results and expert panel responses were in consensus in 71% of the cases. Gambatese et al. (2008) concluded that construction designers play vital role by addressing safety in their designs.

Toole and Carpenter (2011) suggested capital projects should include Prevention through Design (PtD) which is a proactive life cycle approach for improving the safety and health of construction workers. However, they concluded that the diffusion of PtD has been hampered by

several practical factors relating to lack of knowledge; higher costs, industry structure and fear of liability, and practitioners have resisted viewing the issue in terms of ethical obligations. Ekwo and Nigeria suggested collaborating planning with corporate social responsibility (CSR). Collaborative planning resolves conflicts between stakeholders by consensus building and mediation. CSR with collaborative planning will help business promoters benefiting the host community while maximizing their profits. Similarly, CSR indicator system was proposed for construction enterprises by Zhao et al. (2012). A methodology for calculating sustainable score was proposed by Thorpe (2013) by combining economic, environmental and social factors using a life cycle approach. The proposed methodology was demonstrated for selection of roads. The impacts of roads projects on people and their communities are important and are increasingly influencing route alignment decisions and selection of roadway design (Stevenson 1995) .

Gilchrist and Allouche (2005) identified 22 sources of social costs related to construction activities and concluded for developing sustainable oriented construction industry social costs should be incorporated in the bid evaluation process. Since assigning social costs to all impacts is not possible and sometimes leads to inappropriate conclusions, multi criteria approach is required when handing multiple impacts of various characteristics. A framework for assessing the sustainability of concrete materials in Japanese concrete industry by considering social perspectives of stakeholders was proposed by Henry and Kato (2011). Sustainable education as social theme was proposed by Ruano and Cruzado (2012) for construction of buildings. Educational indicator credit rating system was suggested as indicator which reports how well stakeholders were informed and trained in sustainable issues. Valdes-Vasquez and Klotz (2012) proposed a framework for integrating and evaluating social parameters during planning and design phases of construction. The research identified 50 processes and categorized them to six categories of social sustainability. Inputs were taken from 25 experts from academia, industry and government in formulating the 50 processes. They also attempted to incorporate social sustainability into civil engineering education (Valdes-Vasquez and Klotz 2010).

### F.9. Discussions

SLCA of highways is a tool for decision makers' that facilitates selection of various designs, selection of materials, examining construction processes, identifying hotspots, planning measures to mitigate them, etc. The published literature on social sustainability in construction suggests identifying a significant theme, defining associated stakeholder groups, identifying and defining applicable indicators and evaluating on specific social affects in a specified phase of product life cycle. Complete research on SLCA in construction i.e., cradle to grave has not been performed till date but researchers are focusing more on gate to gate (a single phase) studies. With proper justification, the concept of LCA can be applied in studies like specific phases of life cycle, gate to gate, cradle to gate, (Finkbeiner et al. 2006) etc. Fundamentally, methodology and approach exists for application of SLCA in construction but widespread implementation is far from reality (Grießhammer et al. 2006). In SLCA stakeholder management is critical which includes internal human resources (employees, shareholders, suppliers, transporters etc.,) and external human resources (Public) Vallance et al. (2011) . Selection of social criteria and their evaluation is one of the hurdles for executing the concept of social sustainability(Finkbeiner et al. 2010) . For example, construction of new highway can be perceived as a service being provided by a nation (client) but for the construction company (contractor) which is awarded this project will view it is a product. SLCA in this scenario is different for client and contractor. Contractor assessment is more focused on short term influence, i.e., during their construction duration and liability period (planning, construction and maintenance phases), whereas client assessment is more focused on impacts during the use phase of pavement. The social criteria required for these two scenarios will be different.

Most of the research and publications are focused on products while less attention is rendered to services. Even though services and products development have some similar characteristics like management commitment, quality staff, systematic approaches etc., they are significantly different. Specific characteristics of services that differ from product are their intangibility, co-production with customers, simultaneity, heterogeneity and perishability (Fitzsimmons and

Fitzsimmons 1999) . Whether it is a product or service, the concept of social sustainability requires top management involvement. It is their responsibility to focus beyond short-term success and to help its employees clearly understand what is the aim of the organization (Johne 1993). Organizational inertia is more important in the case of new service rather than new product (Nijssen et al. 2006). Participation of each employee or stakeholder towards the development of social sustainability will enhance the human dignity and wellbeing of all stakeholders. Conducting SLCA of highways is different from conducting the same for products. As for products, a functional unit may reflect the overall products social impacts but for pavements a functional unit might not represent the overall social impacts. Since pavements extend over an area and social impacts are a function of geographic location and politics, similar highways may have entirely different social impacts at two different geographical locations. The following Figure F.2 displays the proposed approach for performing SLCA of highways based on above discussion.

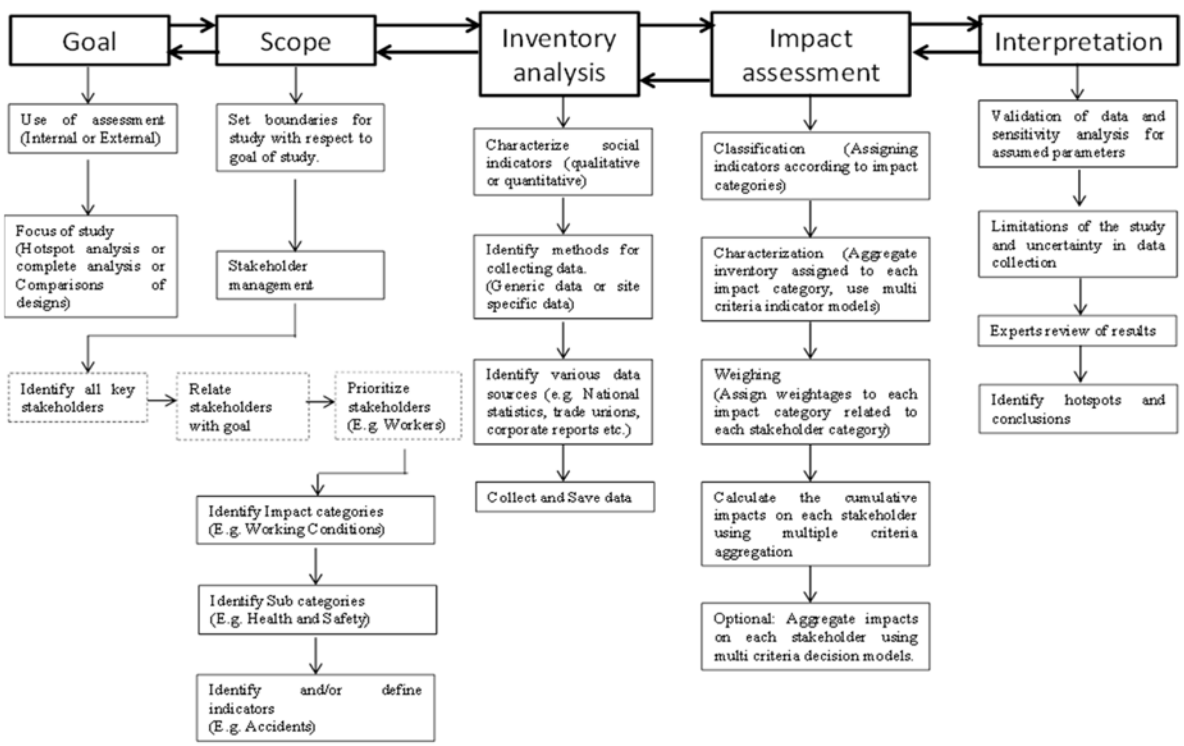


**Figure F.2 Proposed Approach for Social Life Cycle Assessments**

### F.10. Case Study

The proposed methodology was employed for aiding decision makers in selection of various layer thicknesses and materials needed for pavement design. Three equivalent designs were developed for an inbound as well as outbound annual average daily traffic (AADT) of 61,236 in 2014, which is increasing annually at a rate of 0.75% and traffic consists of 10.4% of trucks. The wearing courses for designs are dense graded asphalt concrete (DGAC), open graded asphalt concrete (OGAC) and Portland cement concrete (PCC) respectively.

Irrespective of the design some social impacts remain constant like migration of people, education of local communities, disruption in local social behaviors, land required for construction etc. There is a necessity to identify the parameters, which should be considered that have impact on sustainability determination. There are various social impacts which are solely because of pavement type like noise, accidents, discomfort to the public due to construction, urban heat island effect etc. Traffic noise is considered in this study as a social indicator because traffic noise has acute impacts on human health and leading factor for noise emission is tire pavement interaction. Since the designs considered in the present study have different surface properties, the traffic noise emitted can be used as a parameter to distinguish the pavements. Table F.1 displays the parameters considered in the present study in line with proposed method. It is a known fact that traffic noise has various impacts on humans like negative impacts on health, degeneration of real estate value, impacts on social interactions, etc. but there is no exact impact pathway which establishes the relation between them to traffic noise. However, Federal highway administration (FHWA) provided certain limits to traffic noise and threshold for residential (exterior) is 67 decibels average in an hour as determined by FHWA. This threshold is used in this present study for analysis of various pavements for 30 years. To accomplish the estimation of noise, the Traffic Noise Model (TNM) 2.5 was employed. FHWA along with the John A Volpe National Transportation Systems center, Harris Miller & Hanson, Inc and Foliage Software Systems, Inc. developed Traffic Noise Model (FHWA TNM®). This model can be used to simulate the traffic noise based on the traffic

distribution and speed of the vehicles. Traffic noise was estimated up to 30 years up to 500 feet from edge of the pavement, considering speed of vehicles as 60MPH.

**Table F.1 Outline of Parameters in the Case Study**

| **Phase** | **Parameters** | **Description** |
|---|---|---|
| Goal | Use of assessment | Internal (decision makers), Comparisons of pavement structure designs. |
| | Theme | Human health and well being |
| Scope | Boundary | Use phase |
| | Stakeholders | Local community |
| | Impact category | Human health |
| | Indicator | Traffic Noise |
| Inventory analysis | Method | Assessment of traffic noise levels during use phase of pavement for 30 years using (TNM2.5) |
| Impact assessment | Impact Pathway | No established pathway between noise levels and human health. FHWA recommendation for noise levels is used as thresholds for further assessment. |
| | Characterization | Noise impacts are calculated as costs and emissions arise due to mitigation of traffic noise *i.e.* to keep noise less than threshold as recommended by FHWA. |
| Interpretation | Limitations | TNM will not consider the deterioration of pavement surface performance with time. Noise emissions during construction and maintenance are not considered. |

A noise free wearing course has not been developed yet but the impacts of traffic noise on inhabitants can be reduced by constructing noise barriers. TNM 2.5 has ability to conduct the traffic noise study by inserting barriers on the pavement sides. Different pavement surfaces necessitate the need of barrier walls of various heights, hence, the cost and emissions for constructing and maintenance of barrier walls can be considered as additional burden. Table F.2 displays the barrier height required to reduce traffic noise at various distances from highway. Life

cycle cost analysis for construction and maintenance of barrier walls was conducted for all highway types. In addition, global warming potential and energy consumed for constructing barrier walls was also performed as shown in Table F.3. The costs, emissions and energy consumption can be considered as a social impact that aid decision makers in pavement design selection.

**Table F.2: Summary of Barrier Height Required to Reduce Traffic Noise at Various Distances from Pavements**

| Design | Surface Type | No Barrier | Barrier height in feet required to reduce traffic noise at distance | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Distance in Feet from pavement(noise below 67db) | 50ft | 100ft | 200ft | 300ft | 400ft | 500ft |
| 1 | DGAC | 400 | 16 | 13 | 9 | 4 | 0 | 0 |
| 2 | OGAC | 350 | 14.5 | 12 | 7 | 2.5 | 0 | 0 |
| 3 | PCC | 450 | 18 | 15 | 10 | 5 | 2.5 | 0 |

It is evident from the results in Table F.2 and Table F.3 that Design 2 produces lowest traffic noise compared to other designs. But with increase in traffic each year, the Design 2 also exceeds the limit, necessitating a noise barrier to dissipate the traffic noise on inhabitants. Even though Design 2 exhibits lower impacts and costs, it is erroneous to state it as the sustainable design as many other factors should be considered in the decision-making. Hence, social assessments provide necessary inputs required for decision-making.

### F.11. Conclusions

It is evident that SLCA is an emerging science and its full-fledged application in construction industry needs concentrated effort. Efforts are being made to address social sustainability in construction through various ways but lack of a standard procedure and regulations from authorities has resulted in dispersed approach. Compared to construction, manufacturing industry is advanced in conducting SLCA and the methodologies proposed for products can be adapted to construction. However, amendments are required while adapting methodologies, like selection of social indicators, data collection techniques, functional units etc.

A case study was performed for selecting pavement design based on the traffic noise as a social indicator. Although an outline is proposed, further effort is needed to include SLCA in highway material design and construction.

**Table F.3 Summary of Inputs for Decision Makers**

| METHODOLOGY | Distance in feet from pavement | Designs | | | Trend | Difference between designs | |
|---|---|---|---|---|---|---|---|
| | | D1 | D2 | D4 | | D1 Vs D2 | D2 Vs D3 |
| Life Cycle Cost Analysis | 50 | $2,717,734 | $2,462,947 | $3,057,451 | | $254,788 | -$594,504 |
| | 100 | $2,208,159 | $2,038,301 | $2,547,876 | | $169,858 | -$509,575 |
| | 200 | $1,528,725 | $1,189,009 | $1,698,584 | | $339,717 | -$509,575 |
| | 300 | $679,434 | $424,646 | $849,292 | | $254,788 | -$424,646 |
| | 400 | $0 | $0 | $424,646 | | $0 | -$424,646 |
| Life Cycle Assessments (GWP in ton $CO_2$ e) | 50 | 1066 | 951 | 1224 | | 115 | -272 |
| | 100 | 840 | 768 | 989 | | 72 | -222 |
| | 200 | 194 | 426 | 627 | | -232 | -201 |
| | 300 | 86 | 149 | 299 | | -63 | -151 |
| | 400 | 0 | 0 | 149 | | 0 | -149 |
| Life Cycle Assessments (Energy consumed in million British thermal units) | 50 | 20551 | 18638 | 23103 | | 1,913 | -4,464 |
| | 100 | 16725 | 15449 | 19276 | | 1,276 | -3,827 |
| | 200 | 3666 | 9071 | 12898 | | -5,405 | -3,827 |
| | 300 | 1660 | 3331 | 6520 | | -1,672 | -3,189 |
| | 400 | 0 | 0 | 3331 | | 0 | -3,331 |

NOTES
In LCCA discount rate of 4% used to convert future costs in present worth.
It is likely that noise levels are influenced by other factors such as street traffic,surface material of building,slope of road way, weather conditions etc.
TNM doesn't considers the reflections of noise within structures and also not considers the deterioration of pavement surface.

**No Barrier Analysis**

| Design | Distance in ft from pavement (traffic noise below threshold) |
|---|---|
| 1 | 400 |
| 2 | 350 |
| 3 | 400 |
| 4 | 450 |

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# Appendix G

The material of this appendix, is a technical manuscript entitled "Noise as a social impact indicator for selection of sustainable pavements", was submitted for possible publication to the Journal of Cleaner Production. The manuscript is under review.

# Appendix.G. Noise as a Social Impact Indicator for Selection of Sustainable Pavements

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## G.1. Abstract

The selection of pavement structural design based on social sustainability principles is often ignored due to difficulty in quantification of social issues (like violation of labor rights), throughout the life cycle of pavement. The impact of social factors are also often ignored because unavailability of raw data (due to politics, geography, culture, etc.) or complexity of integrating (measure, aggregate, and compare) society wide impacts. Thus, Social Life Cycle Assessment (SLCA) is still at nascent stage and there does not yet exist a prevailing framework for performing SLCA especially for highway infrastructure. One social indicator that can be reasonably quantified is impact of noise (due to tire pavement interaction) that can influence selection of structural design. The noise levels can influence real estate value, reduce neighborhood social interaction, and can have adverse health effects which may lead to relocation of residents. Thus, this study focusses on identifying and quantifying feasible social indicators (noise) to provide decision makers an insight on differentiating various pavements at the designing and planning phases.

A case study on traffic noise was performed on various pavement types designed for similar geographical location and service life (30 years) using Federal Highway Administration (FHWA) Traffic Noise Model (TNM) version 2.5. Detailed analysis of an increase of noise level every year and up to 30 years was calculated at various distances from pavements, which provided an insight to, how the traffic noise exceeded the threshold of 67 dbA. To reduce noise levels, noise barriers walls were designed at different distances and the cost associated for constructing and maintaining

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noise barriers was included as a social cost. Similarly, environment impacts due to the construction and maintenance of noise barriers can be also considered as social emissions. Social costs and social emissions could provide information for decision makers in the selection of pavement type.

### G.2. Introduction and need for the study

The concept of sustainability is an emerging science and efforts are being made to incorporate sustainability in highways. Federal Highway Administration (FHWA) ("FHWA | Sustainable Highways Initiative | Overview," 2015.)., defines a sustainable highway should satisfy lifecycle functional requirements of societal development and economic growth while striving to enhance the natural environment and reduce consumption of natural resources. It is evident from the definition that the concept of sustainability is multifaceted and a systematic approach is required to address it. Many researchers come to an understanding that the sustainable development stands on three pillars namely economic, environment and social.

Sustainability is context sensitive and there is no universally accepted approach to measure pavement sustainability, as each application demands a unique approach. The fundamental issues in sustainable pavements are: What, When, and How, to measure sustainability? FHWA released a technical report in 2014 (U.S. Department of Transportation, Federal Highway Administration, 2014.) in which how to measure sustainability was briefly discussed. According to this report, there are four general sustainable measurement methods applicable to pavement:

1. Performance Assessment: Assessing overall pavement performance in relation to its intended function and specified physical attributes deemed necessary to meet that function.
2. Life Cycle Cost Analysis (LCCA): Evaluate the total cost of an investment option over its entire life.
3. Life Cycle Assessment (LCA): LCA, a still emerging technique, can be used to analyze and quantify the environmental impacts of a product, system, or process.

Pavement LCA results must be carefully scrutinized since their data sources and system boundaries tend to vary between individual tools and studies.

4. Rating Systems: Rating systems are essentially lists of sustainability best practices with an associated common metric. Rating systems can vary greatly in quality and use; in its simplest form, a rating system can count every best practice equally (e.g., all worth one point), in which case the rating system amounts to a tally of the number of best practices used.

Each measuring method is applicable at different phase of a project. Typically, impacts due to a pavement in its life time is thoroughly evaluated through life cycle assessments during planning and design phase of a pavement. This approach assists the decision makers to understand how each phase of life cycle impacts the sustainability of a pavement. Economic and environmental impacts due to a pavement design have been evaluated through Life Cycle Cost Analysis (LCCA) and Life Cycle Assessments (LCA), respectively. These assessments helps in comparing alternative designs and select the best suitable design. The review of information indicated that most of the research has been focused on economic and environment parameters while giving less emphasis on the social component of sustainability. Ignoring social dimension in decision-making may lead to erroneous decisions; therefore, social impacts needs to be assessed in a pavement's life cycle. Social Life Cycle Assessment (SLCA) is a systematic process which uses the best available science to collect best available data to report on social impacts (positive and/or negative) in product life cycles from extraction (cradle) to final disposal (grave). The scope (the life cycle) and the methodology (a systematic process of collecting and reporting about social impacts and benefits) are both key aspects (Benoît et al., 2010). SLCA can be assimilated with other LCA's and it will facilitate decision makers in making sustainable decisions. In spite of the importance of social impacts in decision-making, it is often ignored due to various challenges as discussed below.

### G.2.1. Challenges in Conducting SLCA

The following are some of the challenges associated with SLCA:

1. Accounting all social issues like creation of local jobs, impacts on the health and education of local communities, disruption of community social behaviors, workforce safety and well-being, human rights etc., is impractical (Schmidt et al., 2004).
2. Even though the SLCA is theoretically possible, it is multi-discipline and multi-dimensional which requires involvement of professionals from various disciplines like psychology, environmental sociology, engineering, human geography etc., to bridge the gaps in theoretical concepts pertaining to social impacts.
3. There is a lack of standard procedure and guidelines for conducting SLCA due to non-availability of data bases.
4. It is a challenging task to identify and quantify social impacts due to high capital and time requirement.

The following are the contributions from this study:

- SLCA is still an emerging tool and its implication is ahead in manufacturing sector compared to construction. Thorough literature review was performed on SLCA in other sectors and an approach was proposed to perform SLCA for highways (Approach for conducting SLCA).
- A case study was performed in selecting pavement design by employing proposed framework and using noise as a social indicator. A procedure for selecting a social impact indicator is demonstrated (Case Study).

Selected literature on social sustainability in construction is discussed at the end of the paper (G.8 Related Work).

### G.3. Approach for Conducting SLCA

To conduct SLCA, there is no standard or internationally recognized code of practice. Various researchers UNEP-SETAC Life Cycle Initiative (2009), Benoît et al., (2010), Hunkeler, (2006), Paragahawewa et al., (2009), and Weidema (2005) have suggested using approach similar to LCA. However, SLCA differs from LCA because SLCA demands to set more priority on the process and integration of stakeholder positions (Grießhammer et al., 2006). In line with ISO 14040 (International Organization for Standardization, 2006), and ISO 14044 (International Organization for Standardization, 2006) related to LCA, the following phases are expected in the assessments:

- Goal and scope
- Inventory analysis
- Impact assessment
- Interpretation

Based on the review of information, an approach is proposed for performing SLCA (Figure G.1). Normally the assessment is performed as a top down approach starting with goal of the study. But the analysis can be adjusted if assessment is hampered at any phase, so assessment drives back forth from one phase to other until the total assessment becomes feasible.

Even though the proposed approach is similar to LCA, it is slightly modified to suit SLCA. The following sections contain detailed explanation on how the LCA phases can be adapted to SLCA.

#### G.3.1. Goal and Scope Definition

The focus of the study depends on this phase as it lays steps to what is desired to achieve with SLCA method. Typically the goal of the SLCA can be to:

- Compare alternative products, processes, or designs, and
- Identify the hotspots in a products life cycle or in a process etc.

The essence of SLCA is to compute impacts on people (stakeholders) due to a product (pavement) throughout its life. Project stakeholders are the people who have a concern for success of the project and the environment in which the project operates (Olander, 2006). According to Olander, the stakeholders can be essentially classified into two categories: 1) Internal (who are actively involved in the project) and 2) External (who are affected by the project). Typically for a construction project, the internal key stakeholders are clients, workers, consultants, contractors and external stakeholders are shareholders associated with the internal stakeholders, local, and global community. As the scope for conducting a detailed analysis on stakeholders is enormous, it necessitates a defined scope based on the context of the study.

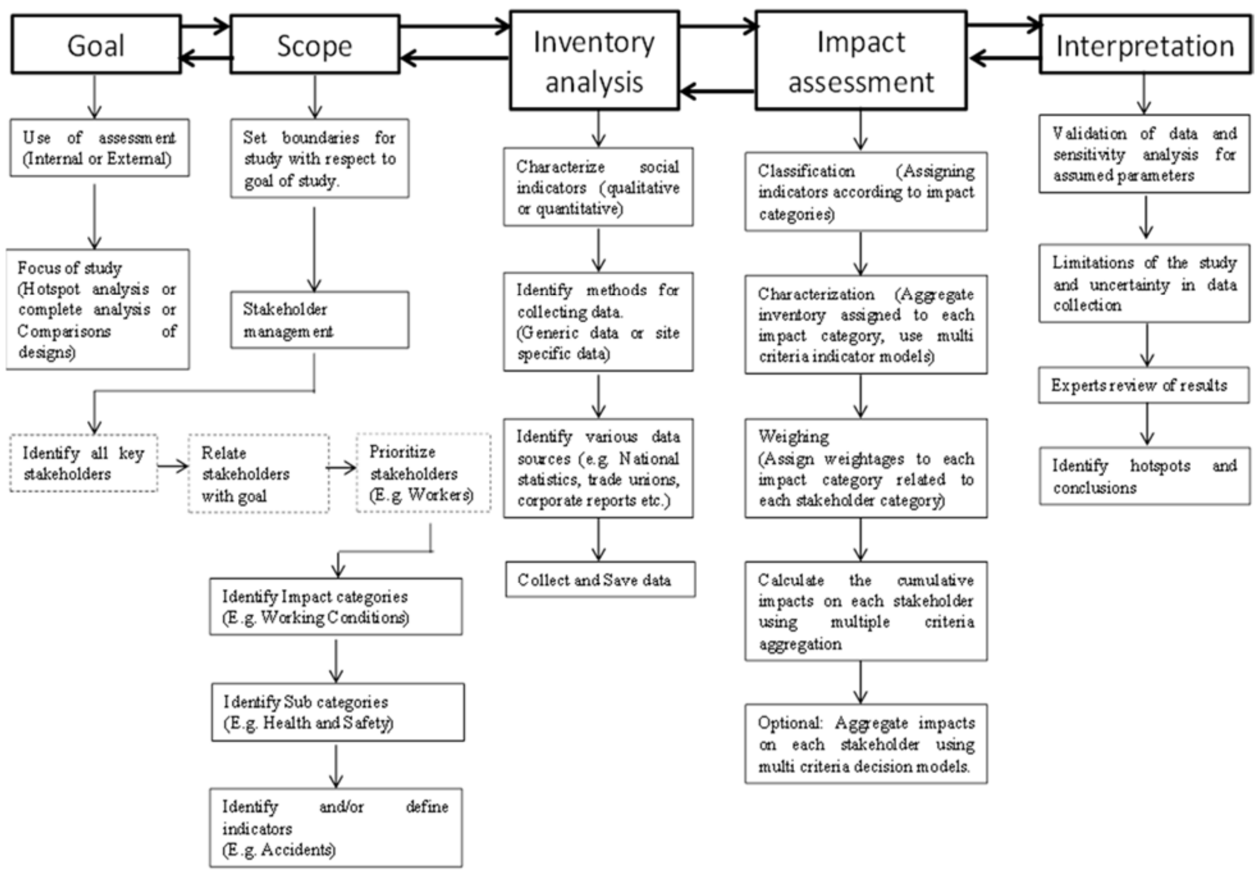


**Figure G.1 Proposed Approach for SLCA in Construction**

The stakeholder management can be a key step in scope definition. The impacts on people (stakeholders) due to a highway in its life time are numerous. It is impractical to assess the impacts

on all people effected by highway, in addition all people are not subjected to similar impacts. For instance, the impacts on highway construction workers will be entirely different in comparison to impact of highways on local community. It is paramount to identify the key stakeholders that are related with Goal of study. Besides, one should also consider the time, cost, and availability of data pertaining to social impacts on the selected stakeholders, quality of data, and association of impacts on goal of the study. Thus, the scope of the study shall be defined such that it balances these factors.

After setting goal and scope one should identify the impact categories like labor rights, health and safety, community impacts etc. that portrays impacts on selected stakeholders. After identifying the social impact categories, allied subcategories needs be defined. For example, labor rights may have several subcategories, like child labor, gender equity, force labor, etc. Next step is to identify the social impact indicators that describe the subcategories.

### G.3.2. Inventory Analysis

In the inventory phase, data is collected based on goal and scope definition. Social impact categories or subcategories have to evaluate through a set or single social indicator. Social indicators acts as a measure for social impacts that selected in scope definition. It is important to note that all social impact indicators are not always quantitative. Selection of social indicators is dependent on the impacts that are being analyzed. According to (Weidema, 2006), the requirement for a good social indicator is that it permits quantification of the extent (incidence or prevalence) as well as duration and severity of the considered aspect. The selection of social indicators should be based on availability of data related to indicator, quality of available data, and possess a valid impact pathway between indicator and the impact category.

### G.3.3. Impact Assessment

In the impact assessment phase, inventory data should be modeled into impacts. Presently, there is no standard social impact assessment method, however, the impact assessment methodology used in LCA can be adjusted to SLCA.

As per ISO 14044 (International Organization for Standardization, 2006), the impact assessment consists of four steps: classification, characterization, normalization and analysis of data quality. In classification, step inventory results are assigned to relevant impact categories. The aim of characterization is to aggregate inventory data within same impact category (International Organization for Standardization, 2006). In SLCA, the characterization models are more complex than LCA as many social impacts cannot be aggregated using traditional quantitative methods (Dreyer et al. 2010). Very few researchers have attempted characterization of social impacts. (Norris, 2006) proposed to use life cycle attribute assessment for impact assessment because attributes of the process are more important than measured quantities per unit of process output. The attributes may be like child labor free processes, fair trade certification, etc.

Dreyer et al. (2010) proposed a multi criteria indicator model for assessing the social impact categories based on a score card and implemented it in six companies. This indicator evaluates the efforts of a company to mitigate social issues and it delivers a score which represent the company's performance aggregated over the life cycle of product. (Weidema, 2006) suggested a characterization indicator Quality Adjusted Life Years (QALYs), which is an accumulation of all impacts towards the reduction of average well-being life. According to Weidema, each social indicator has a severity and duration and by accruing number of occurrences of incidence, their duration and severity, the total impact i.e., reduction in well-being can be estimated. (Hunkeler, 2006) used working hours as indicator to estimate social impacts. The salary made through working hours may be spent to improve impact categories like housing, health care, education and necessities. The research on characterization of social impacts is more dispersed and lack of consensus in the published literature indicates the need for further research.

Normalization step is considered optional in impact assessment and it makes sense only with the quantitative results (Grießhammer et al., 2006). The outcomes from social indicators are related to a reference system i.e., in relation to total impacts in a region or company. The reason for employing weighting is to simplify impact assessment output. Weighting aspires at rating

different impact categories against each other to determine their significance with respect to the goal of SLCA. Apportioning weightages to impact categories is a complex task as it involves multiple factors and experts. Due to the subjectivity involved in assigning weightages to impact categories (Rogers and Seager, 2009), it is considered as an optional step. We suggest usage of multi criteria decision models in addressing the weightages.

#### G.3.4. Interpretation

Interpretation phase is defined as "the process of assessing results in order to draw conclusions" and the process has the following objectives: "to analyze the results, reach conclusions, explain the limitations of the study provide recommendations and report adequately"(UNEP-SETAC Life Cycle Initiative, 2009).

### G.4. Case Study

To demonstrate the proposed methodology, four equivalent pavement designs were developed as shown in Figure G.2. Equivalent design implies that each alternative will be designed to perform equally, and provide the same level of service, over the same performance period, and has similar life-cycle costs (Stephanos,P.J, 2008). Out of the four designs three were flexible pavement designs which were designed using FPS 21. The other design was Continuously Reinforced Concrete Pavement (CRCP) designed using the AASHTO Design Guide. The design software were selected based on the recommendations of the Texas Department of Transportation pavement design guide (Russel Lenz.W, 2011). Each of the design consisted of six-lane highway (three lanes on each side) and has an Annual Average Daily Traffic (AADT) of 61,236 on each side, as per 2014 traffic count. The traffic consists of 10.6% of trucks and 89.4% of passenger cars. The annual growth of traffic is assumed to be 0.75% and pavements is designed for 30 years. Subgrade conditions were considered the same for all the pavements. The three flexible pavement designs varied in their material composition and thickness of layers. On average, the flexible pavement is anticipated to have two rehabilitations during a 30 year period while the rigid pavement is anticipated to have no major rehabilitation. Design 4 does not require maintenance up

to 30 years as per design; however, a minor maintenance (replacing two panels for every lane mile at 20 years) for rigid pavement is assumed in the study. The LCA of these four pavement alternatives was performed for one geographical location (El Paso, Texas).

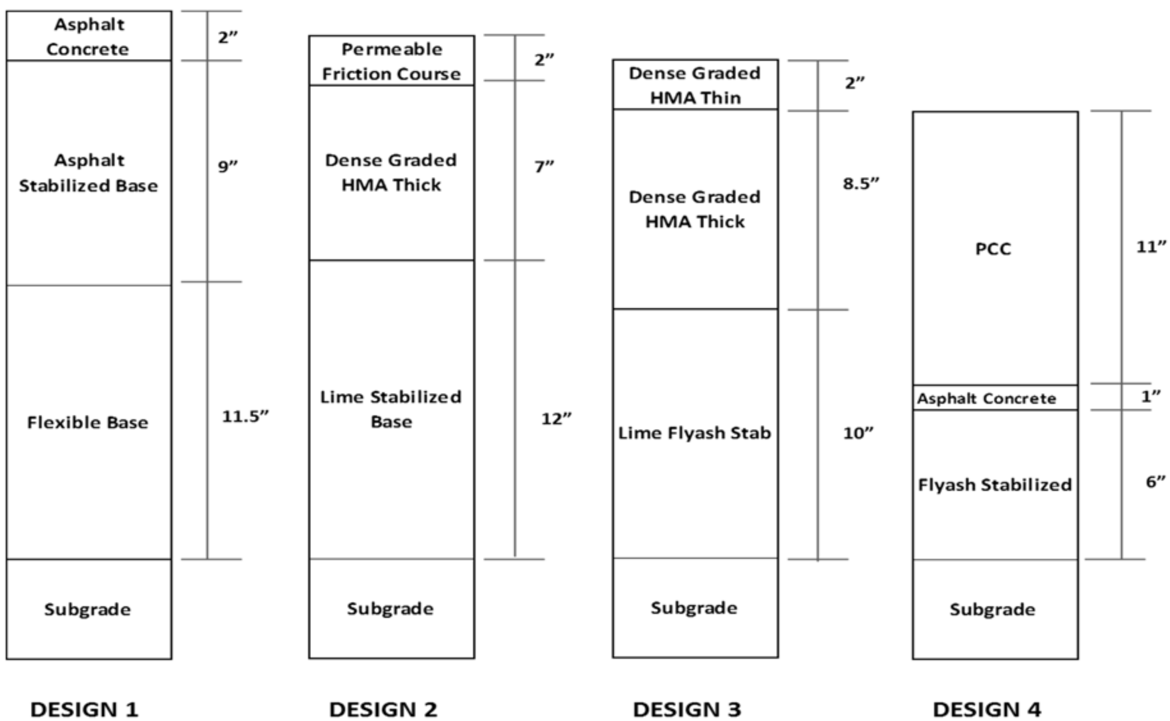


**Figure G.2. Alternative Pavement Designs**

Initial analysis was performed with no barriers and noise was estimated using TNM 2.5 for every year AADT starting from 2014 to 2044. Only 8 percent of AADT is considered for estimating the average hourly noise as the peak traffic hours have traffic around 8 percent on a typical day. The speed of vehicles is considered as 60 miles per hour. After preliminary analysis, noise levels were estimated by considering a noise barrier wall (NBW) at the edge of the shoulder. The noise levels were estimated up to 500 feet from the pavement edge for predicted traffic from 2014 to 2044. The whole process was repeated for barrier walls up to 20 feet high. Study was performed on three different pavement surfaces, considering Design 1 and Design 3 have similar

surface course. Permeable friction course of Design 2 is similar to open graded friction course in TNM model.

In the Table G.1, the outline of the present analysis and the appropriateness of selecting the parameters is shown and explanation is provided in the following sections.

**G.4.1. Goal & Scope of Case Study SLCA**

The present study is focused on assisting decision makers in selection of sustainable structural designs of pavements. Highways will have significant impacts (positive or negative) on numerous people like workforce, local communities, global community, owners, etc. Usually pavements are designed for 30 to 50 years of life in which the construction and maintenance activities will be around 3-5 years, which indicates that the local community is one the most impacted stakeholder in a pavements life. This study is focused on estimating the impacts on local community and sustaining "Human health and Well-being" is considered as social theme. Upon appraising the published literature on social sustainability, SLCA and other tools to compute social impacts "traffic noise" is considered as a social impact indicator. The selection of the indicator is based on feasibility of conducting the inventory analysis and the association of indicator with stakeholder and social theme. The following section vindicates the selection of traffic noise as a social impact indicator.

**G.4.2. Why Noise as a Social Impact Indicator?**

Noise relates to the exposure of a target to unwanted sound produced by a source (Cucurachi.S 2014). In a life cycle of a pavement, "noise" is emanated at all phases. Noise effects on humans can be classified into three general categories ("Noise and Hearing Conservation Technical Manual Chapter: Appendix I:C. Effects of Excessive Exposure," 2015)

1. Primary effects: Acoustic trauma, tinnitus, noise induced temporary threshold shift (NITTS) and noise induced permanent threshold shift (NIPTS).
2. Effects on Communication and performance: Difficulty understanding speech, annoyance, difficulty concentrating, reduced efficiency, adverse social behavior.

3. Other effects: Quickened pulse rate, abnormal secretion of hormones, muscle tension, loss of sleep, fatigue etc.

**Table G.1 Outline of Parameters Used in the Present Study**

| **Phase** | **Parameters** | **Description** |
|---|---|---|
| Goal | Use of assessment | Internal (decision makers), Comparisons of pavement structure designs. |
| | Theme | Human health and well being |
| Scope | Boundary | Use phase |
| | Stakeholders | Local community |
| | Impact category | Human health |
| | Indicator | Traffic Noise |
| Inventory Analysis | Method | Assessment of traffic noise levels during use phase of pavement for 30 years using traffic noise model (TNM2.5) |
| Impact Assessment | Impact Pathway | No established pathway between noise levels and human health. FHWA recommendation for noise levels is used as thresholds for further assessment. |
| | Characterizati on | Noise impacts are calculated as costs and emissions arise due to mitigation of traffic noise i.e to keep noise less than threshold as recommended by FHWA. |
| | Normalization | Some environment impacts are normalized with respect to an annual passenger vehicle emissions in 2014. |
| Interpretation | Limitations | TNM doesn't consider the deterioration of pavement surface performance with time.<br>Noise emissions during construction and maintenance are not considered. |

The two psychosocial effects of road-traffic noise (i.e., annoyance and sleep disturbance) have been associated with negative health outcomes and may lead to the development of certain chronic diseases (Kim et al., 2012). It was predicted that 109,967 people would be at risk of being highly annoyed, with 19,621 people at risk for high levels of sleep disturbance for Fulton County GA (Kim et al., 2012). Similar results in other urban areas indicate that it may be important for the public's health to update existing noise related policies or develop new ones to control and abate noise concerns in urban communities (Minho Kim 2012). Surveys show that frequency of

complaints from noise increases with the size of cities, and that exposure to noise is inversely related to family income, with those on lower levels of income being the most exposed to ambient noise (Bernhard et al. 2005). Exposure of noise for longer period of time may cause hearing loss and adverse health effects such as high blood pressure and hypertension. It may also cause speech interference, sleep disturbance, annoyance and a loss of the quality of life (Bernhard et al., 2005). In addition to the health impacts, noise affects real estate and property values; the scale of impact varies according to the nature of land uses. It is apparent that noise impacts the human health and well-being of the community. Hence, traffic noise can be a potential social indicator that relates to human health and well-being.

### G.4.3. How Traffic Noise from Pavements can be a Social Indicator?

Pavement life cycle typically consists of the following phases: materials extraction, construction, use, maintenance and rehabilitation. Emission of noise occurs at all phases of life. Emissions during all phases except use phase are from machinery and equipment. During use phase, the sources of highway traffic noise are engine/drivetrain noise, exhaust noise, aerodynamic noise and tire/pavement interaction noise (Bernhard et al., 2005). Pavement traffic noise is mostly noise generated by the engine of the vehicle, but noise produced by frictional contact between the vehicle and the air, as between tires and the road surface, exceeds engine noise at speeds higher than 50 km/h (31 mph) for passenger cars and at speeds higher than 80 km/h (50 mph) for trucks (Muzet, 2007). In normal conditions, the vehicles average speed will be higher than 50 mph on highways, so the predominant source of traffic noise is tire pavement interaction. As pavement can be designed with different surface properties, the noise emitted will also be different for various pavements. This differentiating factor can be valuable for decision makers in selecting pavements.

### G.4.4. Inventory Analysis (How Traffic Noise from Pavements can be Quantified?)

In the inventory analysis, the data related to traffic noise needs to be estimated. The most common statistical descriptor for traffic noise is Leq. It is a time weighted average. A 1-hour Leq is usually used by the Federal Highway Administration (FHWA) to determine traffic noise

impacts. To predict highway noise levels for aiding compliance with policies and procedures under FHWA regulations, FHWA along with the John A Volpe National Transportation Systems center, Harris Miller & Hanson, Inc. and Foliage Software Systems, Inc. have developed Traffic Noise Model (FHWA TNM®). The first version 1.0 was released in March 1998 and later on modified multiple times; the current version 2.5 was released in April 2004. TNM can calculate noise level and help in modelling barriers at any location from roadway by providing required inputs like vehicle count, pavement geometry, surface types, and vehicle speeds etc. Four types of pavement surface layers can be considered in TNM namely Average, open graded asphalt concrete (OGAC), Portland cement concrete (PCC) and dense grade asphalt concrete (DGAC). However the current FHWA policies nominate to use "average" pavement as surface type. Other types of surfaces can be enabled for research purposes. In addition, FHWA doesn't recommend use of quieter pavements as noise abatements.

The TNM model with vehicle speed, distance of receptor point from center of the road, ground classification (soft vs hard ground) and counts of different vehicle types (i.e., passenger cars, medium trucks, and heavy trucks) to estimate the hourly equivalent noise level .Henceforth, noise due to tire pavement interaction can be accounted throughout the use phase of a pavement using TNM 2.5. Traffic noise was estimated at various distances (50, 100, 200, 300, 400, and 500 feet) from edge of the pavement. The noise levels were estimated at a height of 5feet from ground level.

#### G.4.5. Impact Assessment

In impact assessment phase the inventoried noise data requires to be characterized into meaningful impacts. It is evident that noise effects human health but, exact impact pathway between noise levels to type of ailment (human health) is not well established. Considering the nature of impacts of traffic noise on humans and lack of well-established process to characterize the impacts, this study proposes use of an indirect impact assessment method as explained below.

The impacts of noise can be reduced on humans by regulating the severity of traffic noise. Noise comprises of three indivisible traits: source, propagation and receiver. Abatement of noise can be done by controlling any of the above traits.

- The best way to control noise is at the source. Noise generated from pavements are from various sources like engine noises, pavement-tire interaction, etc. Quieter cars such as electric vehicles (EVs) and hybrid electric vehicles (HEVs) are being developed recently which can reduce the noise from cars. To mitigate, pavement-tire interaction, efforts are being made to develop quieter pavements like open graded friction courses, open grade concrete etc.
- Since the generated sound propagates from source to the receiver, noise abatement structures are being used to break the path of sound propagation for minimizing impact of noise on receivers (humans).
- Noise at receivers end is being abated by using sound proof windows, sound proof walls etc.

If a pavement design is used as the only way of noise abatement, the effectiveness of pavement surface in reducing noise will diminish with time. On contrary, NBW typically provide similar amount of noise reduction for an extended time even if the noise levels increase with pavement ages (Donavan, 2013). Hence, noise abatement, by using of NBW, reduces the impact on receivers and is ideal because it can provide same level of service for years.

FHWA recommended noise abatement criteria for different activity locations (auditoriums, residential, hotels etc.). For example, FHWA recommends the exterior of residential areas should have noise level below 67 dbA Leq. By using the recommendations of FHWA as threshold limits and modeling the noise levels with different barrier walls through TNM 2.5, one can evaluate the height of barrier walls required for each pavement design to keep the traffic noise levels below limits at specified distance from pavement. As each design necessitates different NBW, the cost associated for constructing and maintaining noise barriers can be included as a social costs.

Similarly, environmental impacts, due to the construction and maintenance of noise barriers, can be considered as social emissions. Social costs and social emissions could provide information for decision makers in the selection of pavements.

#### G.4.6. Interpretation

It is important that the decision makers understands the inadequacies in the study. For example, this research is devoted for only one particular stakeholder (local community), one phase (use) and one impact category. This study is not a comprehensive study of all social impacts. This study does not suggest the best pavement design rather it provides decision maker specific information. The TNM model doesn't considers the deterioration of pavement surface with time, which can influence design of noise barrier walls.

### G.5. Traffic Noise Assessment

Traffic noise assessment was performed for various pavement designs as per the above mentioned approach. The traffic noise levels at various distances from the edge of the pavement for Design 4 are shown in Figure G.3. Since 67 decibels has been recommended by FHWA as a threshold, it is evident that the noise levels are below the threshold limit only after 400 feet from edge of the all the pavement types selected for analysis.

To minimize noise levels closer to pavements, NBW of different heights, at 50 ft. from pavement, were considered and the estimated noise levels are shown in Figure G.4 for Design 4 (PCC). The data suggests that the noise levels were significantly lower with NBW of 15 ft. or higher. Additionally, the noise barrier walls (NBW) below 5ft. were not able to significantly reduce the noise levels. The traffic noise levels with respect to various barrier heights for a distances up to 500 ft. for thirty years (2014 to 2044) were also evaluated for pavement designs of Figure G.2. The results obtained are summarized in Table G.2.

The summarized data estimates that there is no need for NBW 450 ft. away from the pavement as the noise level is lower than 67 dbA for the four selected pavement designs. Among evaluated pavement design, the OGAC surface produces lowest levels of noise and doesn't require

NBW 350 ft. away from the pavement. The maximum required height of NBW is 18 feet closer to the pavement (50 ft. from the edge) for Design 4. Further impact analysis was implemented on calculating the life cycle cost analysis and life cycle assessments for construction and maintenance of NBW and is included in the following sections.

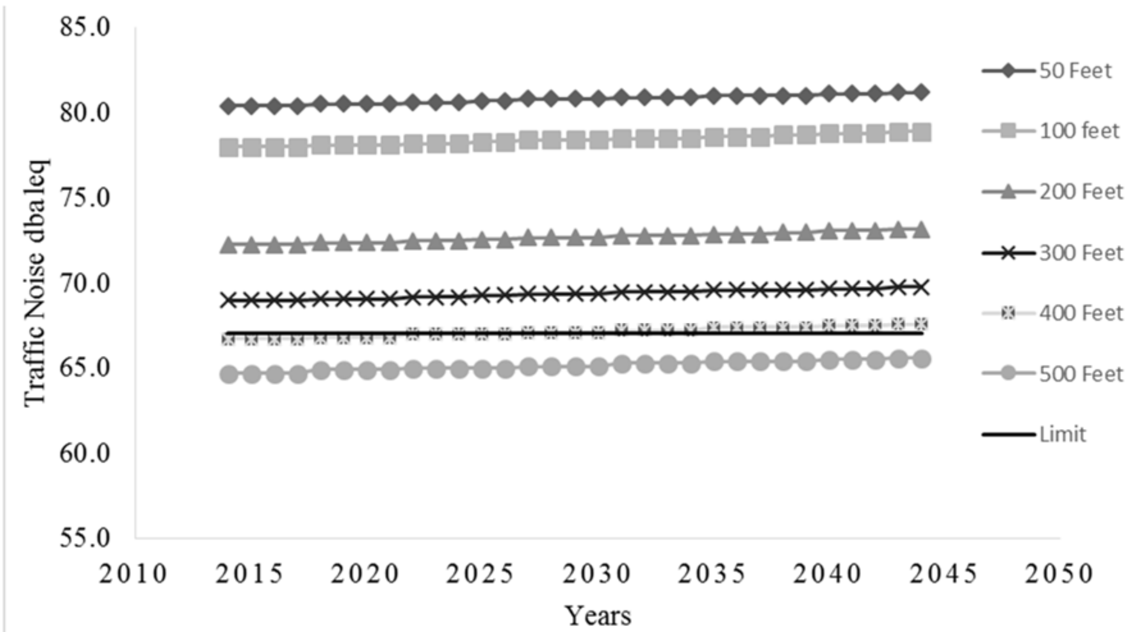


**Figure G.3 Traffic Noise from Edge of Pavement Design 4 (PCC) with No Barriers**

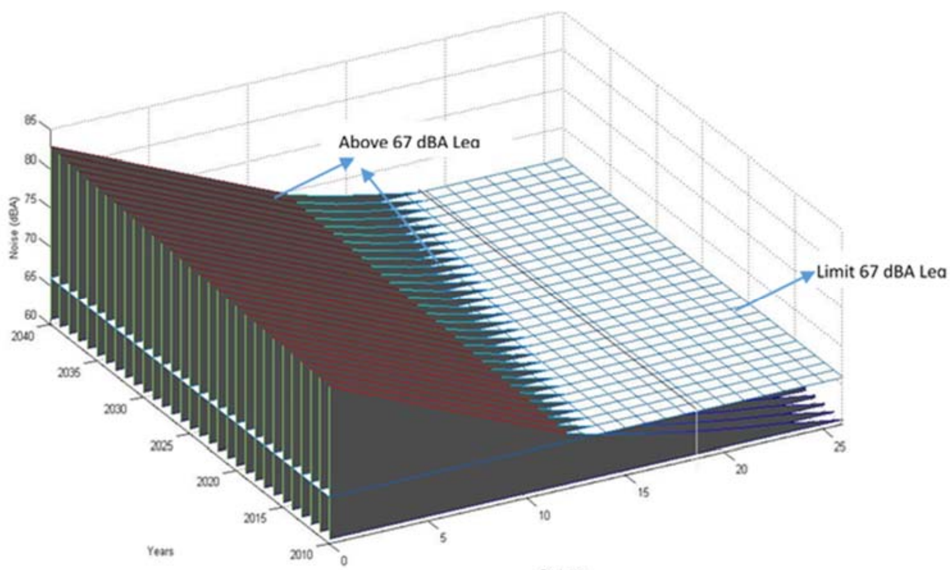


**Figure G.4 Traffic Noise Levels at 50 feet from Edge of Pavement (for Design 4)**

### G.5.1. Impact Assessment

#### *G.5.1.1. Life Cycle Cost Analysis (LCCA)*

Life cycle costs refer to all costs which are involved in the provision of a NBW during its complete life cycle. LCCA needs to estimate the various costs in a NBW life cycle like initial construction costs, maintenance costs, etc., and discount the anticipated costs to net present worth (NPW). If LCCA is being used to compare various designs, the discount rate and analysis period should be same.

**Table G.2 Influence of NBW Height at Various Distances from Pavements**

| Design | Surface Type | No Barrier | Barrier height in feet required to reduce traffic noise at distance | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Distance in Feet from pavement(noise below 67db) | 50ft | 100ft | 200ft | 300ft | 400ft | 500ft |
| 1 | DGAC | 400 | 16.0 | 13.0 | 9.0 | 4.0 | 0.0 | 0.0 |
| 2 | OGAC | 350 | 14.5 | 12.0 | 7.0 | 2.5 | 0.0 | 0.0 |
| 3 | DGAC | 400 | 16.0 | 13.0 | 9.0 | 4.0 | 0.0 | 0.0 |
| 4 | PCC | 450 | 18.0 | 15.0 | 10.0 | 5.0 | 2.5 | 0.0 |

Future costs should be estimated in constant dollars and discounted to the present using a real discount rate. For the present study, a discount rate of 4% was considered for discounting future costs into present worth. The costs for initial construction for the present study was taken from the average low bid prices of El Paso district published by Texas department of Transportation (TxDOT) ("Average Low Bid Unit Prices," 2014). The cost of barrier walls is $30 per square foot in 2014. In addition to the construction, some periodic maintenance was assumed in order to compare various designs. The maintenance includes removal of graffiti every year (assumed 1 percent of walls needs graffiti removal at a price of 1$ per square foot), surface maintenance (includes aesthetics of walls assumed every 10 years at a price of 1$ per square foot) and replacement of damaged barrier walls (assumed 1% walls needs replacement every 5 years and cost is $30 per square foot). The NPW for constructing NBW/mile for various designs at

specific distances were calculated and displayed in the Figure G.5. As anticipated, the cost of NBW is highest for Design 4 and lowest for Design 2.

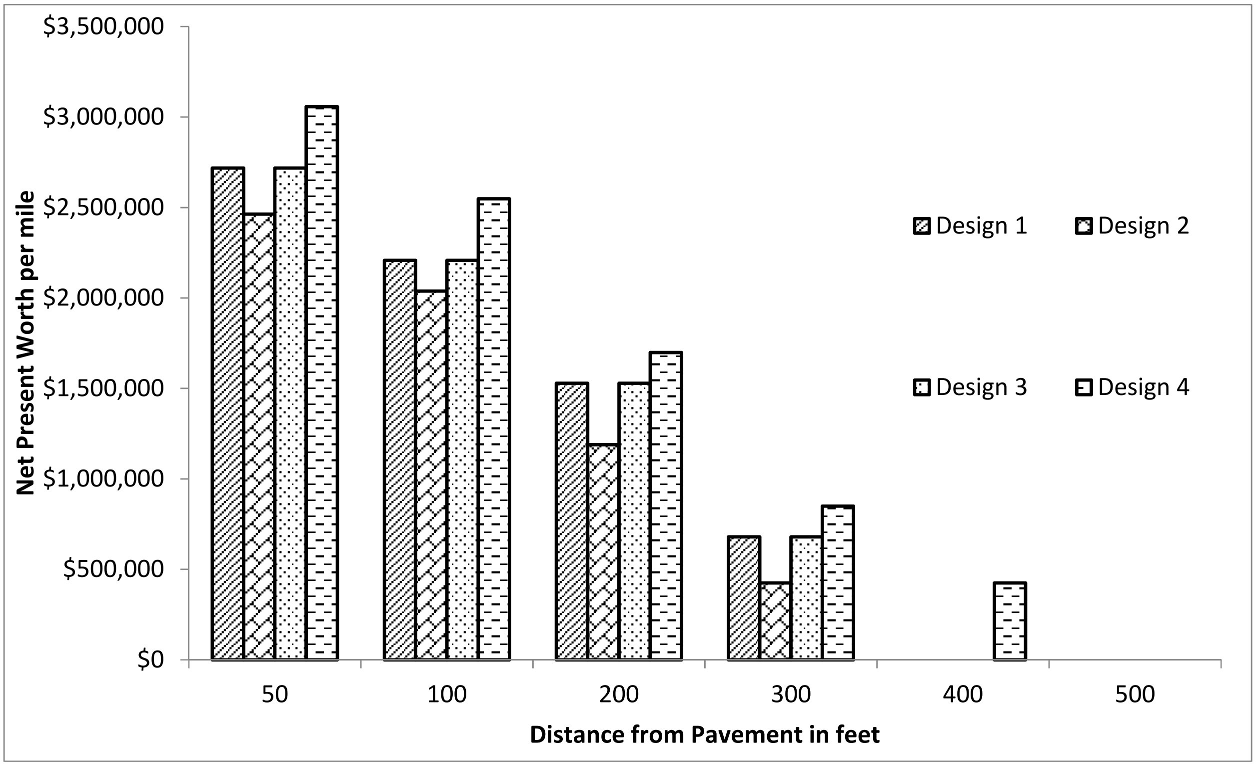


**Figure G.5 NPW of NBW for Various Designs**

### *G.5.1.2. Life Cycle Assessments*

The impacts on environment due to construction of NBW was also evaluated in Life Cycle Assessment (LCA). The design assumptions are based on design guide of highway NBW (Klingner et al., 2003).In this study, NBW was assumed to be precast wall panels mounted between steel posts, which are 20 feet apart. The wall thickness is 4 in. and compressive strength of concrete is assumed to be 2,000 psi. Quantities for constructing NBW walls for various pavement designs were calculated. Emissions were calculated for extraction, manufacture and transportation of wall materials as well. The Greenhouse Gases Regulated Emissions and Energy Use in Transportation (GREET) model was used as the main data source for assessment. GREET includes numerous fuel pathways and existing pathways in the model can be modified as per the requirements. For

example, electricity is required in the concrete batch plant, electricity production data was available in GREET model (for US) but emission data for production of electricity was modified based on the electricity production mix of Texas (U.S.Energy Information Administration 2014).

Energy consumption and air emissions for manufacturing of cement, diesel, natural gas and steel were selected as the U.S average values provided in GREET model. The other main source of emissions is transportation of raw and processed materials to required locations. The transportation energy and emissions can be modelled using GREET model. In this study for estimating emissions during transportation, a 20 ton capacity truck with full front haul and empty back haul is assumed with fuel (diesel) consumption of 5.3 miles per gallon. The  displays the sources of emissions considered for concrete production in this study. An upstream emission considers the energy expended and emissions released for producing materials. Processes like concrete mixing and aggregate crushing were not available in GREET model, therefore, these processes were added based on the field data, for concrete plants data on fuel and electricity use were from Life Cycle Inventory of Portland Cement Concrete (Marceau et al., 2007) and for aggregate crushing from Greenhouse Gas Emissions Inventory CEMEX Jesse Morrow Mountain Plant (ENVIRON International Corporation San Francisco 2009) . The hauling distances were assumed as displayed in Figure G.6 and natural gas for use in concrete batch plant is assumed to be conveyed through pipe lines around 100 miles from refinery. A distribution loss of 7.2% for electricity was considered in the study (Technology Options for the Near and Long Term 2003). The emissions by combustion of fuels in concrete plant were taken from United States Environmental Protection Agency (Eastern Research Group 1998) (United States Environmental Protection Agency 1996) (Eastern Research Group, 1998). Diesel is considered as the fuel used in trucks for transporting materials. Upstream analysis of diesel used for trucks is also considered in the study.

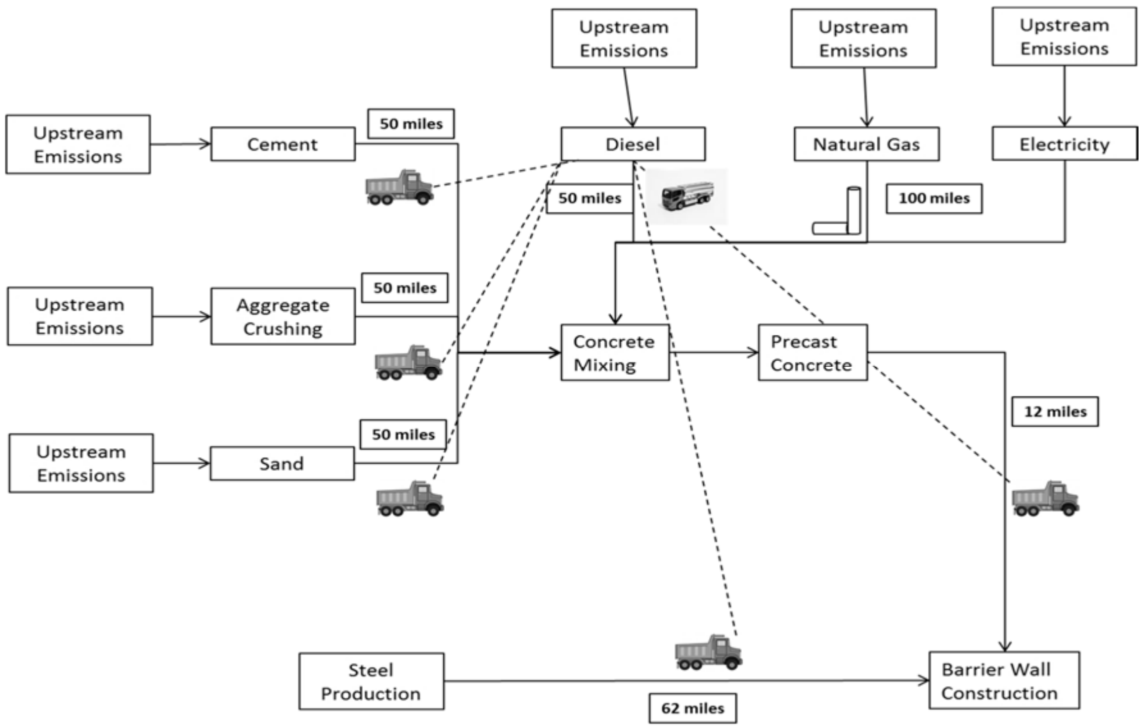


**Figure G.6 Outline of Emissions Considered from Various Sources in LCA of NBW**

Inventory of ten pollutants (carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), volatile organic compounds (VOC), carbon monoxide (CO), particle matter ($PM_{10}$ and $PM_{2.5}$), Sulphur dioxide ($SO_2$), nitrogen oxides (NOx), sulfur oxides (SOx)) and energy consumption were accumulated for constructing NBW of different heights as required by various designs to keep noise below the thresholds. The next step is to convert the classified inventory of each impact indicator into an equivalent scale. For example, various emissions that are contributing towards GWP should be transformed into carbon dioxide equivalents ($CO_2e$). The process of converting various pollutants in an impact category to a common scale is called characterization in LCIA and the factors required to transform the emissions are called characterization factors. These conversion factors were provided by the EPA's impact assessment Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) (United States Environmental Protection Agency 2015) which strives in attaining consistency in environmental decision-making.

The inventory of pollutants were characterized into Global Warming Potential (GWP), Eutrophication (EUT), Smog (SMOG), Acidification (ACID), and Human Health Criteria Air Pollutants (HHCR) using TRACI.

The characterized results are further processed into meaningful data in normalization step. Normalization relates the aggregated impact categories of an LCA to the macro world in which the service / product is surrounded (Lindeijer, 1996). Generally, normalization is a process of converting different numbers into other numbers that have common unit. In this study the characterized impacts were compared with annual passenger car impact ("Greenhouse Gas Emissions from a Typical Passenger Vehicle,"2014.).

The energy consumption is not characterized and normalized into fossil fuel depletion (impact category) due to lack of categorized energy consumption from various fuels. However, energy consumption is proportional to the fossil fuel depletion; hence it should not be ignored.

## G.6. Results

It is recommended to provide a one page summary of analysis to decision makers to apprehend social impacts instantly. Table G.3 shows the summary of this study. The results include the actual impact because of each design as well as the difference between the other designs. As no design is perfectly impact free, the best design in the present context is the one which has less impacts compared to the others. The difference between the costs, emissions, and energy consumption will help the decision makers to differentiate between various designs, which is the purpose of this study.

- It is apparent from Table G.3 that Design 4 causes more traffic noise than the other designs and Design 2 has the lowest impact. In case of no barriers the noise is within threshold after 450 feet from the pavement for Design 4 and 350 feet for Design 2.
- Based on the distance from the edge of pavement where traffic noise abatement is needed, NBW of various heights are required. For brevity, consider 100 feet as the significant distance from the pavement. Barrier analysis was performed to ascertain the

barrier height required for each design type to keep the traffic noise below 67 db. Design 1 and 3 requires 13 feet barrier wall, Design 2 needs 12 feet and Design 4 needs 15 feet wall. In order to amplify the difference between them, life cycle cost analysis and life cycle assessments were performed.

- For every mile construction of barrier wall, Design 4 needs around $510,000 more than Design 2 and $340,000 more than Design 1 & 3. Compared to Design 2, Design 1 & 3 needs $250,000 more per every mile of wall Construction.
- For every mile construction of barrier wall, Design 4 releases 166 tons of CO2 equivalents more than Design 2 and 111 tons more than Design 1 & 3. Similarly, Design 1 & 3 generates 55 tons CO2 equivalents more than Design 2.
- Normalized data helps to present the results in more clear way, for example comparing Eutrophication impact between the Design 2 and Design 4 reveals that the difference is 0.01 tons, which might appear as minimal. However, the difference between the normalized results reveal that the 0.01 tons is equivalent to 32 passenger vehicles annual Eutrophication.
- For every mile construction of barrier wall, Design 4 requires 3,800 mmBTU (million British Thermal Units) of energy more than Design 2 and 2,550 mmBTU more than Design 1 & 3. Similarly, Design 1 & 3 needs 1,276 mmBTU of more energy than Design 2.

- It is evident that Design 4 needs more energy, investment than other designs and produces more emissions, if traffic noise levels impacts needs to be reduced on local community by constructing abatement.

## Table G.3 Inputs to Decision Makers for Traffic Noise Abatement

| Impact Category | Distance in feet from pavement | Actual Impacts | | | | Normalized Impacts (Equivalent Passenger Cars) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | D1 | D2 | D3 | D4 | D1 | D2 | D3 | D4 |
| Global Warming Potential ($CO_2$ e in tons). | 50 | 893.48 | 810.38 | 893.48 | 1004.29 | 183.51 | 166.45 | 183.51 | 206.27 |
| | 100 | 727.27 | 671.87 | 727.27 | 838.08 | 149.38 | 138.00 | 149.38 | 172.14 |
| | 200 | 505.66 | 394.85 | 505.66 | 561.06 | 103.86 | 81.10 | 103.86 | 115.24 |
| | 300 | 228.64 | 145.53 | 228.64 | 284.04 | 46.96 | 29.89 | 46.96 | 58.34 |
| | 400 | 0.00 | 0.00 | 0.00 | 145.53 | 0.00 | 0.00 | 0.00 | 29.89 |
| Eutrophication N-Eq (tons) | 50 | 0.07 | 0.06 | 0.07 | 0.07 | 161.61 | 146.57 | 161.61 | 181.66 |
| | 100 | 0.05 | 0.05 | 0.05 | 0.06 | 131.53 | 121.50 | 131.53 | 151.58 |
| | 200 | 0.04 | 0.02 | 0.01 | 0.02 | 91.42 | 71.36 | 91.42 | 101.45 |
| | 300 | 0.02 | 0.00 | 0.00 | 0.00 | 41.28 | 26.24 | 41.28 | 51.31 |
| | 400 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 26.24 |
| Smog (Nox) tons | 50 | 2.50 | 2.27 | 2.50 | 2.81 | 131.51 | 119.27 | 131.51 | 147.83 |
| | 100 | 2.04 | 1.88 | 2.04 | 2.35 | 107.04 | 98.88 | 107.04 | 123.35 |
| | 200 | 1.57 | 0.64 | 0.41 | 0.64 | 74.40 | 58.09 | 74.40 | 82.56 |
| | 300 | 0.80 | 0.00 | 0.00 | 0.00 | 33.61 | 21.38 | 33.61 | 41.77 |
| | 400 | 0.41 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 21.38 |
| Acidification (H+) tons | 50 | 2.50 | 2.27 | 2.50 | 2.81 | 390.10 | 353.85 | 390.10 | 438.42 |
| | 100 | 2.04 | 1.88 | 2.04 | 2.35 | 317.61 | 293.45 | 317.61 | 365.93 |
| | 200 | 1.42 | 1.11 | 1.42 | 1.57 | 220.96 | 172.63 | 220.96 | 245.12 |
| | 300 | 0.64 | 0.41 | 0.64 | 0.80 | 100.14 | 63.90 | 100.14 | 124.31 |
| | 400 | 0.00 | 0.00 | 0.00 | 0.41 | 0.00 | 0.00 | 0.00 | 63.90 |
| Human Health Criteria Air pollutants (tons) | 50 | 0.15 | 0.14 | 0.15 | 0.17 | 847.88 | 769.27 | 847.88 | 952.70 |
| | 100 | 0.12 | 0.11 | 0.12 | 0.14 | 690.65 | 638.24 | 690.65 | 795.47 |
| | 200 | 0.09 | 0.07 | 0.09 | 0.10 | 481.02 | 376.20 | 481.02 | 533.43 |
| | 300 | 0.04 | 0.03 | 0.04 | 0.05 | 218.97 | 140.36 | 218.97 | 271.38 |
| | 400 | 0.03 | 0.04 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 140.36 |
| Energy Consumption[6] (MMBTU) | 50 | 20551 | 18638 | 20551 | 23103 | | | | |
| | 100 | 16725 | 15449 | 16725 | 19276 | | | | |
| | 200 | 11623 | 9071 | 11623 | 12898 | | | | |
| | 300 | 5245 | 3331 | 5245 | 6520 | | | | |
| | 400 | 0 | 0 | 0 | 3331 | | | | |
| Life Cycle Costs (Present worth in dollars) | 50 | $2,717,734 | $2,462,947 | $2,717,734 | $3,057,451 | | | | |
| | 100 | $2,208,159 | $2,038,301 | $2,208,159 | $2,547,876 | | | | |
| | 200 | $1,528,725 | $1,189,009 | $1,528,725 | $1,698,584 | | | | |
| | 300 | $679,434 | $424,646 | $679,434 | $849,292 | | | | |
| | 400 | $0 | $0 | $0 | $424,646 | | | | |

6 Energy Consumption Values are not normalized.

## G.7. Summary and Conclusions

- As sustainable decision-making involves numerous factors, this study provides a pathway for developing necessary inputs for decision maker in terms of social sustainability.
- Sustainability parameters are dependent on the design selected. Normally, pavement construction devours an enormous amount of resources. The nature and quantity of resources are reliant on the design, so there is a need for a systematic approach for selection of pavement designs.
- In this study a methodology for SLCA is proposed and the proposed methodology is explained through a case study. Noise due to tire pavement interaction is considered as noise impact indicator for differentiating pavement structures. The selection of traffic noise as impact indicator is justified in Case Study.
- Out of four equivalent designs examined in this study, Design 4 has more impacts compared to other designs. However, the best design needs to be selected considering other sustainable parameters like economic and environmental.

### G.7.1. Future research needs

The present study is a baby step in the field social sustainability of pavements and many assumptions were made in this study which needs further research.

- It is assumed that irrespective of pavement type the insertion of barriers of required heights will ensure similar traffic noise levels for inhabitants. This assumption needs to be confirmed by actual field studies.
- Normalization and Weighting steps as proposed in the methodology were not demonstrated in the Case Study. Normalization of social impacts is the area which needs to be addressed. Weighting step involves multi criteria decision analysis and a separate study is required to explain the weighting process. (only partial normalization of environment impact categories is performed).

- It is evident that concrete surface pavement produced higher noise levels compared to asphalt surfaces. However, efforts are focused on developing quieter concrete surfaces. One such effort was done by Purdue University's Herrick Laboratories with collaboration of Portland Cement Association (PCA) and American Concrete Pavement Association (ACPA). They developed a Next Generation Concrete Surface (NGCS) which was quieter than traditional concrete surface (Larry, 2009). Nevertheless, further study in evaluating the long term effectiveness and cost efficiency of NGCS is needed. TNM needs to be updated for the new pavement surfaces.

**G.8. Related Work**

Complete SLCA in construction i.e., cradle to grave has not been performed till date, but researchers are focusing more on gate to gate (a single phase) studies. With proper justification, the concept of LCA can be applied in studies like specific phases of life cycle, gate to gate, cradle to gate, etc. (Finkbeiner et al., 2006).

Upon reviewing the published literature on SLCA in construction it indicates that researchers identified a significant theme and defined associated stakeholders, recognized applicable indicators and evaluated a specific phase of life cycle of project.

- Prevention through design was proposed by (Toole and Carpenter, 2011) as a proactive life cycle approach for improving the safety and health of construction workers.
- The social theme of workforce safety and wellbeing was chosen by (Gatti et al., 2012) and they aimed at using physiological status monitors (PSM) to monitor physical strain in workers who were working in dynamic activities.
- Sustainable education as social theme was proposed by (Ruano and Cruzado, 2012) for construction of buildings. Educational indicator credit rating system was suggested as indicator which reports how well the stakeholders were informed and trained in sustainable issues.

- A framework for integrating and evaluating social considerations during planning and design phases for construction was proposed by (Valdes-Vasquez and Klotz, 2012).
- FHWA TNM 2.1 and 2.5 models were analyzed to determine their functionality and accuracy in Colorado by Colorado Department of Transportation (CDOT) (Hankard et al., 2006). The noise levels were predicted using FHWA models at 42 locations at 13 different sites in Colorado. Predicted noise levels were later compared with measured noise levels. Results showed that TNM 2.5 was accurate to within approximately 2 dB on an average and statistical basis. TNM 2.5 predicted within 3 dB of measured levels at 35 sites (83%). The model is under predicting noise levels by more than 2 dB at distances greater than 300 feet from the roadway (Hankard et al., 2006).
- Noise measurements were conducted in downtown areas in three cities in the United States: Atlanta, Los Angeles and New York City (Lee et al., 2014). (Lee et al., 2014) assessed traffic noise levels in three different cities and noise levels are surprisingly high in all three cities, at or above thresholds associated with adverse health impacts found in other studies. Predictions from noise models that are based on measured traffic data, such as the FHWA's TNM models should correlate well with measured noise levels. They found that TNM model tended to under estimate the average noise levels compared to measured noise levels in each of three cities, the rankings of TNM modeled noise levels were consistent with the measured noise levels, TNM models might be appropriate for use in studies whose goal is to estimate the association between noise levels and health outcomes. However, the tendency of TNM models to underestimate noise exposures may lead to underestimates of the size of populations at risk of health impacts from noise. The underestimate of noise by TNM models may be in real life situation traffic from cross streets and nearby freeways may have contributed to ambient noise measured at sites. Noise reflections from building can be a significant noise contributor in urban areas and TNM models will not accommodate for this contributor.

It is likely that noise levels are influenced by other factors such as street width, height and surface material of buildings, presence of sound wall, green space, slope of road way, tire pavement interaction and weather conditions (Lee et al., 2014).

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## Appendix H

The material of this appendix, is a technical manuscript entitled "Application of Fuzzy Preference Analytic Hierarchy Process (AHP) logic in evaluating sustainability of transportation infrastructure requiring multi criteria decision-making" , was submitted for possible publication to to the Journal of Infrastructure Systems ASCE. The manuscript was assigned a manuscript number ISENG 828R1. The manuscripts is currently under review.

# Appendix.H. Application of Fuzzy Preference-Analytic Hierarchy Process (AHP) Logic in Evaluating Sustainability of Transportation Infrastructure Requiring Multi Criteria Decision-making

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## H.1. Abstract

Selection and construction of sustainable infrastructure is a complex process due to multi-criteria decision requirements. The Analytic Hierarchy Process (AHP) is a widely used multi criteria decision tool in Civil engineering applications. However, the chief drawback of AHP is that it requires large number of inputs (pairwise comparisons) which frequently leads to inconsistency in decision-making. The main objective of this study is to reduce the number of inputs in AHP without compromising consistency. A modified AHP method is proposed and evaluated that uses additive transitivity property of fuzzy preference relations. The proposed method reduces more than 65% of inputs in a typical multi criteria decision model, hence minimizes inconsistency. The effectiveness of the proposed method was verified through a case study for selecting a contractor from six contractors. Inputs were taken from three decision makers for both traditional and proposed AHP, the rankings obtained from the proposed method were compared with traditional AHP. The comparison revealed that the use of lesser number of inputs in conjunction with additive transitive fuzzy preference relations generated consistent judgments in minimal time.

Key Words

AHP, Additive Transitivity Property Fuzzy Relations, Non Parametric Tests.

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## H.2. Introduction

Efforts are being made to incorporate sustainability in decision-making for transportation infrastructure. Sustainable development is a multidimensional concept, which requires inclusion of environmental, social, and economic aspects into decision-making. To make decisions for multidimensional concept, a multi-criteria approach is needed. The Analytic Hierarchy Process (AHP) is a widely used multi-criteria approach for Civil Infrastructure applications (Sayyadi and Awasthi 2012). Various researchers demonstrated the use of AHP in decision-making in Civil Engineering applications. Shapira and Goldenberg (2005) applied AHP in selection of construction equipment by considering various subjective (soft) factors in addition to quantitative factors like costs, etc. AHP was used for the prioritization of pavement maintenance activities by Farhan and Fwa (2009). Farhan and Fwa (2011) also used AHP to prioritize network level maintenance of pavement segments with multiple distresses. Kang and Lee (2007) developed a process for deciding priorities for median barrier installation using AHP on four or more lane highways in Korea. Valeo et al. (2012) analyzed data from surveys to improve bridge security checklist using AHP and new weightages were assigned to each question in the survey. Habtamu et.al(2013) employed AHP for selection of track for light rail transit projects. Gurganus and Gharaibeh (2012) developed a new method for the selection and prioritization of pavement projects with the use of AHP as multi decision-making platform. Johnson and Ozbek (2013) suggested various bridge management components that have well defined goals to aid engineers, managers, and decision makers for effective bridge management components. Sayyadi and Awasthi (2012) used AHP for location planning of pedestrian zones using qualitative data in addition to quantitative data. It is apparent that AHP is being used in various applications in civil engineering for decision-making. The main reasons for wide usage of AHP are its ability to evaluate subjective as well as objective measures, decomposing a complex problem into various hierarchies of criteria (Macharis et al. 2004), and ability to check the inconsistencies in decision maker’s judgments (discussed in the next section). In spite of AHP wide applications and simple analytical efforts, it has following limitations:

1. uncertainty in assigning a crisp value (single point 1,3,5,7,9 etc.) for pairwise comparisons (Wang and Chen 2008),
2. rigorous consistency requirement in pairwise judgments which shifts the focus of decision makers towards satisfying consistency rather than actual judgments (Li et al. 2013 and Lee 2014), and
3. the need for more number of pairwise comparisons with increase in complexity of decision problem (Lee 2014).

According to Kahraman (2008) decision makers often find it difficult to accurately and simultaneously assign a crisp number for pairwise comparison (assign single point for pairwise comparison). To minimize this complexity, Chang (1996) suggested the use of fuzzy numbers instead of crisp numbers and proposed Fuzzy AHP (FAHP) as an extension of conventional AHP. Instead of using a crisp value, FAHP allows decision makers to present their judgments within a reasonable interval. The FAHP method proposed by Chang is one of the widely used methods in decision-making, which uses the extent analysis method in AHP using Triangular Fuzzy Numbers (TFNs) for pairwise comparisons.

Few researchers Pan (2008) and Li and Zou (2011) attempted to include the characteristics of decision makers like experience and confidence of decision makers into AHP using fuzzy principles like α-cut , max min aggregation, and center of gravity, etc. Even FAHP has able to address some issues associated with conventional AHP, the other drawbacks like number of pairwise comparisons and consistency in pairwise judgments still prevailed. To overcome these issues, Herrera-Viedma et al. (2004) proposed to use fuzzy preference relations to increase consistency in conventional AHP. Later, Wang and Chen (2008) adapted fuzzy preference relations in FAHP. Although use of fuzzy preference relations approach had been in existence, suitability of their application for evaluating sustainability of highway infrastructure have not been evaluated. In addition, reliability of fuzzy preference relations in generating consistent judgments needs to be evaluated.

### H.3. Objectives

Based on the above-discussion, the objectives of this study are:

1. evaluate the feasibility of using enhanced AHP (inclusion of fuzzy preference relations and additive transitive property) in decision-making process for evaluating sustainability of transportation infrastructure,
2. the association of enhanced AHP with conventional AHP through statistical tests,
3. the reliability of fuzzy preference relations in AHP in generating consistent judgments, and
4. the extent of percentage reduction of pairwise comparisons.

The basic AHP and FAHP information is included in the following section along with discussion on inclusion of additive transitive property of fuzzy Preference Relations in AHP and FAHP. The assessment of the proposed approach is performed, using a case study, and is included in the case study section. In the end, results of statistical tests, reliability assessment, and level of pairwise comparison assessment is included.

### H.4. Conventional AHP

According to Triantaphyllou and Mann (1995), the AHP is a decision support tool that can be used to solve complex decision problems. To make a decision, the AHP method requires four fundamental steps (Saaty 1980 and 1987; Shapira and Goldenberg 2005; Smith and Tighe 2006; Farhan and Fwa 2009; Farhan and Fwa 2011; Gurganus and Gharaibeh 2012; Lee 2014, and Li et al., 2013), and are discussed in the following sections.

#### H.4.1. Hierarchical Structure

AHP uses multi-level hierarchical structure of objectives, criteria, sub-criteria, and alternatives for decision-making (Triantaphyllou and Mann 1995). The process starts with an objective, and then criteria and sub-criteria (if needed) are selected that characterize the objective. An example of the hierarchical structure for selection of contractor is illustrated in Figure H.1, which will also be utilized in the case study section. The objective of this hierarchical structure is

to identify the best contractor based on four main criteria, namely, Cost, Quality, Safety and Experience. Some of the main criteria were further divided into sub-criteria. For instance, the sub-criteria of cost are tender price, financial references, financial stability, and insurance repairs and warranties. The final level of hierarchy is alternatives. The present example has six contractors, from which the best one needs to be identified.

### H.4.2. Pairwise Comparisons

The success of AHP depends on the input provided by the decision makers. Since input is multidimensional and an absolute value cannot be assigned by decision makers, the input is provided in the qualitative form (based on relative importance) and is expressed in numbers, which most commonly are ratios of integers. In the above example, the objective is to select a contractor based on four criterion:

Cost, Quality, Safety and Experience. A dollar value can be assigned to cost but not to experience (multidimensionality). Similarly, it is difficult to compare cost expressed in dollars with experience, which is an abstract property. However, the relative importance of cost with respect to experience can be established (like cost is more important than experience) in selection of a contractor (relative importance). In other words, the direct association between them is irresolvable, however, the associativity of the criteria can be expressed as relative importance of one criterion over another. For AHP, the decision makers provide relative importance of each alternative in terms of each criterion for comparison and is termed as Pairwise Comparisons. The decision makers provide pairwise judgements typically based on the relative importance scale proposed by Saaty (1980). A modified version of the scale is shown in Table H.1 which is typically given to the decision maker for providing pairwise comparisons. The comparisons provided in the linguistic form are quantified using a scale, which is a one-to-one mapping between the set of discrete linguistics choices available to the decision makers (Table H.1). Pairwise comparisons can also be quantified in fuzzy form, which will be discussed in the later section.

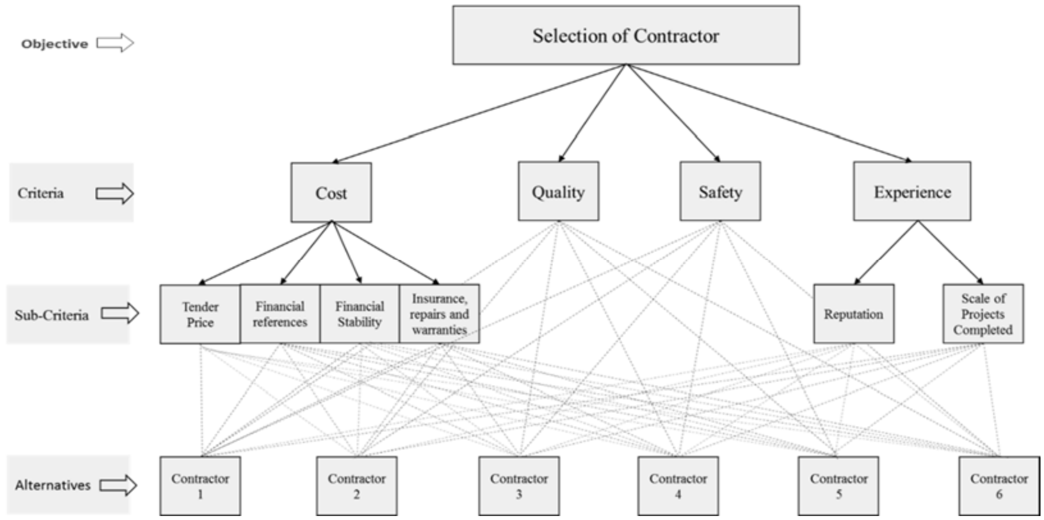


**Figure H.1 Graphical Representation of Hierarchy for Selection of a Contractor**

**Table H.1 Pairwise Comparison Scale (based on Saaty, 1980)**

| Definition (Linguistic Scale) (For inverse relationships use '*1*' before linguistic scale) | Explanation | Numerical Numbers | | Fuzzy Numbers (Chang 1996) | |
|---|---|---|---|---|---|
| | | Crisp Number | Inverse Crisp Number | Triangular Membership functions | Inverse Triangular Membership functions |
| Equally important (EI) | Two activities contribute equally to the objective | 1 | 1.00 | (1,1,3) | (1/3,1,1) |
| Weakly important (WI) | Experience and judgment slightly favors one activity over another | 3 | 0.33 | (1,3,5) | (1/5,1/3,1) |
| Strongly important (SMI) | Experience and judgment strongly favors one activity over another | 5 | 0.20 | (3,5,7) | (1/7,1/5,1/3) |
| Very Strongly more important (VSMI) | Experience and judgment very strongly favors one activity over another | 7 | 0.14 | (5,7,9) | (1/9,1/7,1/5) |
| Extremely more important (AMI) | Experience and judgment absolutely favors one activity over another | 9 | 0.11 | (7,9,9) | (1/9,1/9,1/7) |

### H.4.3. Synthesizing Priorities

The number of pairwise comparisons for each hierarchical level with n factors will be $n(n-1)/_2$. For comparing two criteria Ai and Aj, a pairwise comparison value $a_{ij}$ will be assigned which represents the relative importance of alternative Ai over Aj. Reciprocal property holds well in AHP which means $a_{ji} = {}^1/_{a_{ij}}$. In the above example, the four criteria need six pairwise comparisons (based on crisp numbers) as shown in the matrix (Equation 1). The diagonal elements are equal to 1 and the remaining pairwise comparisons are calculated using the reciprocal property (Equation 2).

$$\begin{pmatrix} & Cost & Quality & Safety & Experience \\ Cost & & 3 & 7 & 3 \\ Quality & & & 7 & 7 \\ Safety & & & & 1/7 \\ Experience & & & & \end{pmatrix}. \quad (\mathbf{1})$$

$$\begin{pmatrix} & \mathbf{Cost} & \mathbf{Quality} & \mathbf{Safety} & \mathbf{Experience} \\ \mathbf{Cost} & \mathbf{1} & \mathbf{3} & \mathbf{7} & \mathbf{3} \\ \mathbf{Quality} & \mathbf{1/3} & \mathbf{1} & \mathbf{7} & \mathbf{7} \\ \mathbf{Safety} & \mathbf{1/7} & \mathbf{1/7} & \mathbf{1} & \mathbf{1/7} \\ \mathbf{Experience} & \mathbf{1/3} & \mathbf{1/7} & \mathbf{7} & \mathbf{1} \end{pmatrix} \quad (2)$$

The weightages associated with each criterion are calculated by normalizing the principal Eigen vector. The principal Eigen value for the above matrix is 4.66 and the corresponding Eigen vector is {0.775, 0.592, 0.062, and 0.211}. Normalization of the Eigen vector will provide weightages associated with each criterion {0.473, 0.361, 0.037, and 0.129}.

### H.4.4. Consistency Ratios (CR)

Consistency signifies the logic that exists between judgments of a decision maker. A matrix of size $(n \times n)$ is considered consistent if $a_{ij} \times a_{jk} = a_{ik}\ \forall\, i, j, k = 1, \dots, n$. In the above example, $(\text{Cost}, \text{Quality}) = 3$ while, $(\text{Quality}, \text{Experience}) = 7$. Therefore, to be consistent $(\text{Cost}, \text{Experience}) = (\text{Cost}, \text{Quality}) \times (\text{Quality}, \text{Experience}) = 3 \times 7 = 21$. Cost should be extremely more important than experience, but it has a value of 3 (weakly important). Thus, the values entered are inconsistent. The AHP process yields a way of measuring the

consistency of the decision maker's preferences, and according to Saaty (1980), the decision maker is completely consistent if the $(n \times n)$ decision matrix satisfies the following conditions

$$\begin{Bmatrix} a_{ij} \times a_{jk} = a_{ik} \ \ \forall \, i, j, k = 1, \dots, n. \\ \lambda_{max} = n \\ CI = 0 \end{Bmatrix} \tag{3}$$

where $CI = \left(\frac{\lambda_{max} - n}{n-1}\right)$ (4)

$\lambda_{max}$ is the principle eigen value, n = number of alternatives, and CI is the consistency index. Satisfying the above condition in AHP is challenging, and to measure the consistency, Saaty (1980) defined a factor known as the consistency ratio as:

$$CR = \frac{CI}{RI} \tag{5}$$

where RI is the average value of CI for random matrices using the Saaty scale obtained by Forman (1990). According to Forman (1990) and Saaty (1980), pairwise comparisons are considered consistent if CR<0.1. The RI for the matrix size 4 is 0.90 while CI for the above example is 0.216. Thus, the CR of the above example is 0.24, which means pairwise judgments are inconsistent. Another approach for checking consistency in the AHP process was proposed by Alonso and Lamata (2006) who suggested that a matrix will be sufficiently consistent if and only if

$$\boldsymbol{\lambda_{max} - n \leq \alpha(\bar{\lambda}_{max}(n) - n)} \tag{6}$$

Where $\boldsymbol{\bar{\lambda}_{max}(n) = 2.7699n - 4.3513}$.

The $\alpha$ is the level of consistency needed ($0<\alpha\leq 1$) and $\lambda_{max}$ is the maximum right eigenvalue. If decision-maker judgments are coherent, then the CR will be in an acceptable range otherwise the decision maker has to modify their inputs, which makes the whole decision-making process more tedious.

### H.5. Fuzzy AHP

The FAHP method proposed by Chang (1996) and Buckley (1985) are widely used methods in decision-making, which uses triangular fuzzy numbers (TFN) for pairwise comparisons. A typical TFN is expressed as (l,m,u) where $l \leq m \leq u$ and m is the modal value and $l, u$ represent the lower and upper bounds of the fuzzy number.

The consistency of judgment using fuzzy consistency analysis was first proposed by Leung and Cao (2000), however, the process was tedious. Fuzzy AHP was also evaluated by Wang and Chen (2008) and concluded that it is unrealistic to expect a decision-maker to provide comparison ratios which are consistent using fuzzy numbers. However, Buckley (1985) has proved that if a reciprocal matrix with crisp number is consistent, then the corresponding matrix by using fuzzy ratios is also consistent.

Table H.1 shows the TFNs used in this study, the modal value of each TFN are kept same as crisp numbers. If the decision matrix with crisp numbers is consistent, the matrix with TFNs with model value same as crisp numbers shall be consistent. The stepwise procedure of FAHP with examples was presented by Chang (1996) and the same procedure is used in calculating the weightages in this study and are discussed in the subsequent sections.

### H.6. Fuzzy Preference Relations Inclusion in AHP and FAHP

Herrera-Viedma et al. (2004) proposed to use the additive transitivity property of fuzzy preference relations to increase consistency. Use of fuzzy preference relations in AHP helps in reducing the number of inputs. This method needs $(n-1)$ pairwise comparisons unlike $n\,(n-1)/2$ inputs required for evaluating $n$ criteria by the conventional AHP. The remaining pairwise comparisons are constructed based on $(n-1)$ inputs by using the additive transitivity property of fuzzy preference relations. The same concept was applied by Wang and Chen. (2008) for improving the consistency of FAHP and they reported success using the method. To comprehend this method, the approach employed by Herrera-Viedma et al. (2004) is discussed followed by approach proposed by Wang and Chen (2008).

### H.6.1. Herrera Viedma Approach

Consider a set of alternatives, $X = \{x_1, x_2, \dots . x_n\}$, associated with a reciprocal multiplicative preference relation $A = (a_{ij})$ for $a_{ij} \epsilon [1/q, q]$ where $q$ is the range of comparison scale . For example, the q for the scale shown in Table 1 will be 9 (maximum) and 1/q will be 0.11 (minimum), which is normalized to a scale of 0 to 1. Then, the corresponding reciprocal fuzzy preference relation, $P = (p_{ij})$ with $p_{ij} \epsilon$ [0,1] associated with A is given as

$$p_{ij} = g(a_{ij}) = \frac{1}{2}(1 + \log_q a_{ij}) \tag{7}$$

For a reciprocal fuzzy preference relation $P = (p_{ij})$, the statements shown in Equation 7 are equivalent. This proposition is very important because it can be used to construct a consistent fuzzy preference relation from the set of $n - 1$ values $\{p_{12}, p_{23}, \dots, p_{(n-1)n}\}$.

The remaining pairwise comparisons are constructed using additive transitive property as shown in Equation 8. Sometimes the constructed preference relation falls in the interval $[-k, 1 + k]$ , $k > 0$ rather than$[0, 1]$. Then, the obtained values can be transformed within the desired range $[0, 1]$ using a transformation function that preserves reciprocity and additive consistency. The transforming function shown in Equation 9 can be used to preserve consistency.

$$\begin{cases} p_{ij} + p_{jk} + p_{ki} = \frac{3}{2}, \forall\, i, j, k \\ p_{ij} + p_{jk} + p_{ki} = \frac{3}{2}, \forall\, i < j < k \\ p_{i(i+1)} + p_{(i+1)(i+2)} + \cdots + p_{(j-1)(j)} + p_{(j)(i)} = \frac{j-i+1}{2}, \forall\, i < j \end{cases} \tag{8}$$

$$f: [-k, 1 + k] \to [0,1], f(x) = \frac{x+k}{1+2k} \tag{9}$$

### H.6.2. Wang and Chen Approach

The Wang and Chen modified Herrera Viedma approach by converting crisp numbers into fuzzy numbers with the help of the equation 10. The other steps of both approaches are similar.

$$\begin{cases} p_{i(i+1)}^{l} + p_{(i+1)(i+2)}^{l} + \cdots + p_{(j-1)j}^{l} + p_{ji}^{u} = \frac{j-i+1}{2}, \forall\, i < j \\ p_{i(i+1)}^{m} + p_{(i+1)(i+2)}^{m} + \cdots + p_{(j-1)j}^{m} + p_{ji}^{m} = \frac{j-i+1}{2}, \forall\, i < j \\ p_{i(i+1)}^{u} + p_{(i+1)(i+2)}^{u} + \cdots + p_{(j-1)j}^{u} + p_{ji}^{l} = \frac{j-i+1}{2}, \forall\, i < j \end{cases} \quad (10)$$

### H.7. Methodology

Based on the above discussion, the different approaches are being proposed for evaluating decision-making process for the proposed case study:

#### H.7.1. Proposed AHP (PAHP) (Method1)

- At each level, (n-1), the pairwise comparisons ($C_1$ vs $C_2$, $C_2$ vs $C_3$ … $C_{n-1}$ vs $C_n$ where $C_1$, $C_2$ …$C_{n-1}$, $C_n$ are criteria) are assigned as linguistic variables.
- Convert the linguistic variables into crisp numbers or fuzzy numbers.
- Convert the $(n-1)$ numbers into fuzzy preference relations using, Eq.(7).
- Remaining fuzzy preference relations are calculated using fuzzy additive transitive property as proposed by Herrera-Viedma (2004) by using Eq.(8) for crisp numbers and Eq.(10) for fuzzy numbers.
- If calculated fuzzy preference relation values are not in the range [0,1] then they can be transformed within desired range using Eq.(9).
- Weightages are calculated for fuzzy numbers by using Changs (1996) Extent analysis method and for crisp numbers methodology proposed by Saaty (1980) is used.

#### H.7.2. Conventional AHP (CAHP) (Method 2)

In this method, the (n-1) pairwise comparisons provided by the decision makers in Method 1 are kept constant.

- Each decision maker was asked to enter the remaining $(n-1)\ (n-2)/2$ judgments as linguistic variables while keeping the $(n-1)$ judgments unchanged.

- The linguistic variables were converted into crisp numbers and the consistency was calculated as proposed by Alonso and Lamata (2006). At each level, inputs are generated four times such that consistency ratio will be 0-5%, 5-10%,10-20% and 20-30% without changing the (n-1) inputs. To achieve this, the input provided by decision makers were modified to generate the required consistency ratios.
- The four weightages at each level for each consistency ratio were calculated using Conventional AHP (CAHP) proposed by Saaty (1980) and saved for future analysis.
- After verifying the consistency ratios, the linguistic variables were converted into fuzzy numbers and weightages were calculated using Chang's Extent analysis method.

### H.8. Case Study

To evaluate the feasibility of proposed AHP and perform statistical assessment, a case study (fabricated) was performed for selecting a contractor (Figure H.1) based on bid data as shown in Table H.2. Inputs for the proposed method were obtained from three decision makers (Decision makers were Texas Department of Transportation employees taking graduate levels courses at the University with experience in Infrastructure projects and were familiar with AHP methodologies). Only 47 pairwise comparisons i.e., $(n-1)$ were required for the proposed methodology in comparison to the traditional approach (133 pairwise comparisons are typically needed for the conventional approach). For pairwise comparisons, linguistic variables were assigned and converted into crisp values or fuzzy numbers as shown in Table H.2. The relative weightages for the six contractors were calculated in two ways (Method1 and Method2) for both fuzzy and crisp numbers.

### H.9. Results and Discussions

The weightages provided by Decision Maker One (D1) are shown in Table H.3 for crisp numbers and Table H.4 for fuzzy numbers. The first ten rows of the tables show weightages assigned by D1 for each criteria and sub-criteria. The weightages for each contractor for criteria and sub-criteria are shown in the remaining rows. The weightages for criteria/alternative are shown

in column 4 for Method1 and the weightages for criteria/alternative are shown in column 5 through 8 for Method2. The pairwise comparisons were modified such that the consistency ratio varied from 0 to 30%. The obtained weightages were then grouped in 0-5% (column 5), 5-10% (column 6), 10-20% (column 7), and 20-30% (column 8) subgroups. The columns 9 through 13 shows ranking of weightages shown in columns 4 through 8. The highest value (weightage) is ranked one and remaining rankings followed descending values of columns 4 through 8. In cases where values were equal, similar rankings were assigned.

**Table H.2 Bid Data**

| Contractor | Tender Price | Failure to complete contract | Financial Stability & references | Cost overruns | Quality | Safety | Experience in local area | Scale of Projects Completed |
|---|---|---|---|---|---|---|---|---|
| Con 1 | $916,672 | 19 | Very Good | 18 | Excellent | Excellent | 5 | 4 |
| Con 2 | $1,399,771 | 13 | Good | 25 | Excellent | Excellent | 5 | 4 |
| Con 3 | $1,342,415 | 21 | Fair | 32 | Fair | Excellent-Good | 18 | 14 |
| Con 4 | $931,980 | 17 | Very good | 38 | Excellent-good | Fair-Poor | 5 | 4 ( 3 projects completed and 1 near completion) |
| Con 5 | $854,540 | 15 | Fair-Poor | 38 | Fair | Poor | 1 | 1 |
| Con 6 | $1,154,620 | 16 | Poor | 40 | Good-Fair | Good | 5 | 4 ( 3 projects completed and 1 near completion) |

For sake of brevity, sub-criteria 'Tender Price' final weightage results for input provided by D1 are discussed here.

- The results suggest that Contractor 5 (C5) has a maximum weightage of 0.350 for Method 1 and 0.445 for Method 2 (CR 0-5%) as shown in Table H.3, for weightages were calculated using the CAHP method. Although the weightage numbers are different due to different analysis techniques, both methods decided in favor of C5 up to a consistency ratio of 10%. The data also suggest that the CAHP method of analysis assigned similar weightages which lead to similar ranking for both methods {Method 1 and Method 2 (CR 0-5% & 5-10%)}. The weightages/ranking changed between the two methods when CR was higher than 10%, which was expected because the CAHP specifies CR to be less than 10% {Saaty (1980)}.

- The results also indicated that C5 was not always ranked highest. For instance, C5 ranked lowest when evaluated for scale of projects completed and safety criteria.
- The results suggest that C5 has a maximum weightage of 0.28 for Method 1 and 0.40 for Method 2 (CR 0-5%) as shown in Table H.4 when weightages were calculated using Chang's extent analysis method. Although the weightage numbers are different due to different analysis techniques, both methods decided in favor of C5 up to consistency ratio of 10%. Comparison of rankings evaluated by the proposed method and CAHP using fuzzy numbers reveals that there was insignificant difference in the first three rankings but considerable difference in the last positions. For instance, out of six contractors, two of them were allotted a weightage of zero under method 2 (0-5% CR) whereas the proposed method generated weightages for all contractors (six different ranks).Although, Fuzzy logic can be used for generating the remaining data for Method 2, the analysis suggested that the n-1 inputs are guiding final weightages.

The final weightages were calculated as per the hierarchy of the problem by averaging the inputs from three decision makers. Figure H.2 displays the final weightages assigned to six Contractors by three decision makers (D1, D2, and D3) using crisp numbers (Figure H.2a) as well as fuzzy (Figure H.2 b). The weightages indicate that Contractors 3, 4, 5, and 6 ranked lower regardless of number type or method of analysis. However, the distinction between Contractor 1 and 2 is not apparent for crisp numbers. For instance, average ranking suggests Contractor 1 should be selected as per Method1 while Method2 suggests Contractor 2 should be selected. The data indicates that the method of analysis governs selection of Contractor 1 or 2. Similar, reversal in ranking was observed for fuzzy numbers as well (Figure H.2 b) Since weightages provided by the decision makers were averaged, the PAHP and CAHP methods are unable to discriminate between the two contractors. To further enhance the discrimination between contractors, Data Envelopment Analysis (DEA) techniques can be performed, in the future, for selection of the contractor.

# Table H.3 Weightages and Ranks Calculation for Inputs Provided by D1 (Conventional AHP)

| Comparison | Criteria /Sub criteria /Alternatives | | Weightage | | | | | Rank | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Method 1 | Method 2 (CR) in % | | | | Method 1 | Method 2 (CR) in % | | | |
| | | | | 0-5 | 5-10 | 10-20 | 20-30 | | 0-5 | 5-10 | 10-20 | 20-30 |
| Criteria | Cost | | 0.43 | 0.53 | 0.58 | 0.54 | 0.47 | 1 | 1 | 1 | 1 | 1 |
| | Quality | | 0.27 | 0.22 | 0.20 | 0.27 | 0.36 | 2 | 2 | 2 | 2 | 2 |
| | Safety | | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 4 | 4 | 4 | 4 | 4 |
| | Experience | | 0.27 | 0.22 | 0.18 | 0.15 | 0.13 | 2 | 2 | 3 | 3 | 3 |
| Sub criteria | Cost | T. P. | 0.40 | 0.54 | 0.60 | 0.53 | 0.52 | 1 | 1 | 1 | 1 | 1 |
| | | F. R. | 0.20 | 0.14 | 0.17 | 0.22 | 0.24 | 2 | 4 | 2 | 2 | 2 |
| | | F.S. | 0.20 | 0.16 | 0.14 | 0.14 | 0.14 | 2 | 2 | 3 | 3 | 3 |
| | | I. R.& W. | 0.20 | 0.16 | 0.09 | 0.10 | 0.09 | 2 | 2 | 4 | 4 | 4 |
| | Experience | R. | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 1 | 1 | 1 | 1 | 1 |
| | | S.P.C. | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 1 | 1 | 1 | 1 | 1 |
| Alternatives | Tender Price (T.P) | Con1 | 0.23 | 0.21 | 0.23 | 0.49 | 0.54 | 2 | 2 | 2 | 1 | 1 |
| | | Con2 | 0.03 | 0.03 | 0.05 | 0.02 | 0.02 | 5 | 5 | 5 | 6 | 6 |
| | | Con3 | 0.03 | 0.03 | 0.03 | 0.02 | 0.04 | 5 | 5 | 6 | 5 | 5 |
| | | Con4 | 0.23 | 0.21 | 0.17 | 0.15 | 0.16 | 2 | 2 | 3 | 3 | 3 |
| | | **Con5** | **0.35** | **0.44** | **0.44** | **0.24** | **0.19** | **1** | **1** | **1** | **2** | **2** |
| | | Con6 | 0.14 | 0.07 | 0.08 | 0.08 | 0.04 | 4 | 4 | 4 | 4 | 4 |
| Alternatives | Financial References (F.R) | Con1 | 0.14 | 0.07 | 0.09 | 0.24 | 0.25 | 3 | 3 | 4 | 2 | 2 |
| | | Con2 | 0.31 | 0.55 | 0.52 | 0.54 | 0.50 | 1 | 1 | 1 | 1 | 1 |
| | | Con3 | 0.11 | 0.06 | 0.10 | 0.05 | 0.06 | 4 | 4 | 3 | 6 | 5 |
| | | Con4 | 0.21 | 0.19 | 0.20 | 0.07 | 0.08 | 2 | 2 | 2 | 3 | 3 |
| | | **Con5** | **0.11** | **0.06** | **0.06** | **0.06** | **0.07** | **4** | **4** | **5** | **4** | **4** |
| | | Con6 | 0.11 | 0.06 | 0.04 | 0.05 | 0.05 | 4 | 4 | 6 | 5 | 6 |
| Alternatives | Financial Stability (F.S) | Con1 | 0.32 | 0.38 | 0.36 | 0.20 | 0.20 | 1 | 1 | 1 | 2 | 2 |
| | | Con2 | 0.20 | 0.15 | 0.18 | 0.12 | 0.16 | 3 | 3 | 3 | 3 | 3 |
| | | Con3 | 0.08 | 0.05 | 0.05 | 0.06 | 0.08 | 4 | 4 | 4 | 6 | 6 |
| | | Con4 | 0.29 | 0.34 | 0.34 | 0.47 | 0.34 | 2 | 2 | 2 | 1 | 1 |
| | | **Con5** | **0.08** | **0.05** | **0.05** | **0.07** | **0.08** | **4** | **4** | **5** | **5** | **5** |
| | | Con6 | 0.03 | 0.03 | 0.03 | 0.08 | 0.13 | 6 | 6 | 6 | 4 | 4 |
| Alternatives | Insurance, Repairs & Warranty (I.R. & W) | Con1 | 0.40 | 0.47 | 0.51 | 0.41 | 0.37 | 1 | 1 | 1 | 1 | 1 |
| | | Con2 | 0.28 | 0.26 | 0.27 | 0.23 | 0.23 | 2 | 2 | 2 | 2 | 2 |
| | | Con3 | 0.15 | 0.13 | 0.11 | 0.12 | 0.18 | 3 | 3 | 3 | 3 | 3 |
| | | Con4 | 0.07 | 0.06 | 0.04 | 0.08 | 0.07 | 4 | 4 | 4 | 5 | 6 |
| | | **Con5** | **0.07** | **0.06** | **0.04** | **0.10** | **0.08** | **4** | **4** | **4** | **4** | **4** |
| | | Con6 | 0.03 | 0.03 | 0.02 | 0.07 | 0.07 | 6 | 6 | 6 | 6 | 5 |
| Alternatives | Quality | Con1 | 0.24 | 0.27 | 0.36 | 0.37 | 0.31 | 1 | 1 | 1 | 1 | 2 |
| | | Con2 | 0.24 | 0.27 | 0.26 | 0.29 | 0.33 | 1 | 1 | 2 | 2 | 1 |
| | | Con3 | 0.06 | 0.04 | 0.04 | 0.07 | 0.06 | 5 | 5 | 5 | 4 | 6 |
| | | Con4 | 0.24 | 0.27 | 0.22 | 0.18 | 0.18 | 1 | 1 | 3 | 3 | 3 |
| | | **Con5** | **0.06** | **0.04** | **0.04** | **0.05** | **0.07** | **5** | **5** | **5** | **6** | **4** |
| | | Con6 | 0.16 | 0.10 | 0.09 | 0.05 | 0.06 | 4 | 4 | 4 | 5 | 5 |
| Alternatives | Safety | Con1 | 0.31 | 0.34 | 0.39 | 0.33 | 0.34 | 1 | 2 | 1 | 1 | 1 |
| | | Con2 | 0.31 | 0.36 | 0.35 | 0.22 | 0.24 | 1 | 1 | 2 | 3 | 2 |
| | | Con3 | 0.20 | 0.17 | 0.15 | 0.11 | 0.12 | 3 | 3 | 3 | 4 | 4 |
| | | Con4 | 0.04 | 0.03 | 0.03 | 0.04 | 0.07 | 5 | 5 | 5 | 6 | 6 |
| | | **Con5** | **0.04** | **0.03** | **0.03** | **0.06** | **0.07** | **5** | **5** | **6** | **5** | **5** |
| | | Con6 | 0.10 | 0.07 | 0.06 | 0.25 | 0.17 | 4 | 4 | 4 | 2 | 3 |
| Alternatives | Reputation (R ) | Con1 | 0.19 | 0.14 | 0.14 | 0.19 | 0.16 | 2 | 2 | 4 | 3 | 3 |
| | | Con2 | 0.19 | 0.14 | 0.17 | 0.09 | 0.07 | 2 | 2 | 2 | 4 | 5 |
| | | Con3 | 0.29 | 0.45 | 0.44 | 0.36 | 0.37 | 1 | 1 | 1 | 1 | 1 |
| | | Con4 | 0.15 | 0.12 | 0.15 | 0.08 | 0.09 | 4 | 4 | 3 | 5 | 4 |
| | | **Con5** | **0.02** | **0.03** | **0.03** | **0.03** | **0.06** | **6** | **6** | **6** | **6** | **6** |
| | | Con6 | 0.15 | 0.12 | 0.09 | 0.25 | 0.25 | 4 | 4 | 5 | 2 | 2 |
| Alternatives | Scale of Projects Completed (S.P.C) | Con1 | 0.20 | 0.16 | 0.16 | 0.28 | 0.24 | 2 | 2 | 3 | 2 | 1 |
| | | Con2 | 0.20 | 0.16 | 0.19 | 0.10 | 0.09 | 2 | 2 | 2 | 5 | 6 |
| | | Con3 | 0.31 | 0.45 | 0.43 | 0.29 | 0.20 | 1 | 1 | 1 | 1 | 3 |
| | | Con4 | 0.15 | 0.12 | 0.12 | 0.12 | 0.16 | 4 | 4 | 4 | 4 | 4 |
| | | **Con5** | **0.03** | **0.03** | **0.03** | **0.05** | **0.10** | **6** | **6** | **6** | **6** | **5** |
| | | Con6 | 0.10 | 0.07 | 0.07 | 0.16 | 0.21 | 5 | 5 | 5 | 3 | 2 |

## Table H.4 Weightages and Ranks Calculation for Inputs Provided by D1 (Fuzzy AHP)

| Comparison | Criteria /Sub criteria /Alternatives | | Weightage | | | | | Rank | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Method 1 | Method 2 (CR) in % | | | | Method 1 | Method 2 (CR) in % | | | |
| | | | | 0-5% | 5-10% | 10-20% | 20-30% | | 0-5 | 5-10 | 10-20 | 20-30 |
| Criteria | Cost | | 0.41 | 0.45 | 0.51 | 0.43 | 0.38 | 1 | 1 | 1 | 1 | 2 |
| | Quality | | 0.29 | 0.29 | 0.28 | 0.33 | 0.40 | 3 | 2 | 2 | 2 | 1 |
| | Safety | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4 | 4 | 4 | 4 | 4 |
| | Experience | | 0.30 | 0.26 | 0.22 | 0.24 | 0.22 | 2 | 3 | 3 | 3 | 3 |
| Sub criteria | Cost | T. P. | 0.25 | 0.25 | 0.41 | 0.51 | 0.49 | 1 | 1 | 1 | 1 | 1 |
| | | F. R. | 0.25 | 0.25 | 0.31 | 0.32 | 0.34 | 1 | 1 | 2 | 2 | 2 |
| | | F.S. | 0.25 | 0.25 | 0.20 | 0.12 | 0.13 | 1 | 1 | 3 | 3 | 3 |
| | | I. R.& W. | 0.25 | 0.25 | 0.08 | 0.05 | 0.04 | 1 | 1 | 4 | 4 | 4 |
| | Experience | R. | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 1 | 1 | 1 | 1 | 1 |
| | | S.P.C. | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 1 | 1 | 1 | 1 | 1 |
| Alternatives | Tender Price (T.P) | CON1 | 0.23 | 0.29 | 0.26 | 0.36 | 0.52 | 3 | 2 | 3 | 1 | 1 |
| | | CON2 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 5 | 5 | 5 | 4 |
| | | CON3 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 6 | 5 | 5 | 5 | 4 |
| | | CON4 | 0.23 | 0.28 | 0.29 | 0.21 | 0.24 | 2 | 3 | 2 | 3 | 2 |
| | | **CON5** | **0.28** | **0.40** | **0.32** | **0.31** | **0.24** | **1** | **1** | **1** | **2** | **3** |
| | | CON6 | 0.16 | 0.02 | 0.12 | 0.11 | 0.00 | 4 | 4 | 4 | 4 | 4 |
| Alternatives | Financial References (F.R) | CON1 | 0.15 | 0.00 | 0.08 | 0.40 | 0.43 | 3 | 3 | 4 | 2 | 2 |
| | | CON2 | 0.24 | 0.75 | 0.56 | 0.60 | 0.52 | 1 | 1 | 1 | 1 | 1 |
| | | CON3 | 0.13 | 0.00 | 0.09 | 0.00 | 0.00 | 6 | 3 | 3 | 4 | 4 |
| | | CON4 | 0.20 | 0.25 | 0.27 | 0.00 | 0.06 | 2 | 2 | 2 | 3 | 3 |
| | | **CON5** | **0.15** | **0.00** | **0.00** | **0.00** | **0.00** | **4** | **3** | **5** | **4** | **4** |
| | | CON6 | 0.14 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 3 | 5 | 4 | 4 |
| Alternatives | Financial Stability (F.S) | CON1 | 0.23 | 0.43 | 0.38 | 0.28 | 0.22 | 2 | 1 | 1 | 2 | 2 |
| | | CON2 | 0.19 | 0.20 | 0.26 | 0.20 | 0.19 | 3 | 3 | 3 | 3 | 3 |
| | | CON3 | 0.13 | 0.00 | 0.00 | 0.02 | 0.11 | 5 | 4 | 4 | 5 | 4 |
| | | CON4 | 0.23 | 0.38 | 0.36 | 0.44 | 0.29 | 1 | 2 | 2 | 1 | 1 |
| | | **CON5** | **0.13** | **0.00** | **0.00** | **0.02** | **0.08** | **4** | **4** | **4** | **5** | **6** |
| | | CON6 | 0.10 | 0.00 | 0.00 | 0.04 | 0.11 | 6 | 4 | 4 | 4 | 5 |
| Alternatives | Insurance, Repairs & Warranty (I.R. & W) | CON1 | 0.28 | 0.45 | 0.53 | 0.33 | 0.26 | 1 | 1 | 1 | 1 | 1 |
| | | CON2 | 0.25 | 0.35 | 0.38 | 0.26 | 0.23 | 2 | 2 | 2 | 2 | 2 |
| | | CON3 | 0.16 | 0.19 | 0.08 | 0.18 | 0.22 | 3 | 3 | 3 | 3 | 3 |
| | | CON4 | 0.12 | 0.01 | 0.00 | 0.11 | 0.12 | 4 | 4 | 4 | 4 | 4 |
| | | **CON5** | **0.11** | **0.00** | **0.00** | **0.11** | **0.11** | **5** | **5** | **4** | **5** | **5** |
| | | CON6 | 0.08 | 0.00 | 0.00 | 0.00 | 0.05 | 6 | 5 | 4 | 6 | 6 |
| Alternatives | Quality | CON1 | 0.22 | 0.29 | 0.32 | 0.35 | 0.31 | 3 | 1 | 1 | 1 | 2 |
| | | CON2 | 0.23 | 0.29 | 0.29 | 0.29 | 0.33 | 2 | 1 | 2 | 2 | 1 |
| | | CON3 | 0.06 | 0.00 | 0.00 | 0.08 | 0.06 | 6 | 5 | 5 | 4 | 4 |
| | | CON4 | 0.24 | 0.29 | 0.28 | 0.28 | 0.27 | 1 | 1 | 3 | 3 | 3 |
| | | **CON5** | **0.07** | **0.00** | **0.00** | **0.00** | **0.00** | **5** | **5** | **5** | **5** | **6** |
| | | CON6 | 0.18 | 0.14 | 0.12 | 0.00 | 0.03 | 4 | 4 | 4 | 5 | 5 |
| Alternatives | Safety | CON1 | 0.30 | 0.35 | 0.41 | 0.28 | 0.29 | 2 | 2 | 1 | 1 | 1 |
| | | CON2 | 0.33 | 0.38 | 0.38 | 0.23 | 0.22 | 1 | 1 | 2 | 3 | 3 |
| | | CON3 | 0.20 | 0.24 | 0.21 | 0.20 | 0.19 | 3 | 3 | 3 | 4 | 4 |
| | | CON4 | 0.03 | 0.00 | 0.00 | 0.01 | 0.04 | 5 | 5 | 4 | 6 | 6 |
| | | **CON5** | **0.00** | **0.00** | **0.00** | **0.03** | **0.04** | **6** | **5** | **4** | **5** | **5** |
| | | CON6 | 0.13 | 0.03 | 0.00 | 0.26 | 0.23 | 4 | 4 | 4 | 2 | 2 |
| Alternatives | Reputation (R ) | CON1 | 0.19 | 0.21 | 0.20 | 0.20 | 0.17 | 2 | 2 | 3 | 3 | 3 |
| | | CON2 | 0.19 | 0.19 | 0.21 | 0.14 | 0.05 | 3 | 3 | 2 | 4 | 5 |
| | | CON3 | 0.25 | 0.37 | 0.34 | 0.29 | 0.33 | 1 | 1 | 1 | 1 | 2 |
| | | CON4 | 0.16 | 0.13 | 0.16 | 0.10 | 0.10 | 5 | 4 | 4 | 5 | 4 |
| | | **CON5** | **0.04** | **0.00** | **0.00** | **0.00** | **0.00** | **6** | **6** | **6** | **6** | **6** |
| | | CON6 | 0.17 | 0.10 | 0.09 | 0.28 | 0.35 | 4 | 5 | 5 | 2 | 1 |
| Alternatives | Scale of Projects Completed (S.P.C) | CON1 | 0.19 | 0.24 | 0.23 | 0.23 | 0.19 | 2 | 2 | 3 | 2 | 3 |
| | | CON2 | 0.19 | 0.22 | 0.24 | 0.12 | 0.14 | 3 | 3 | 2 | 5 | 5 |
| | | CON3 | 0.24 | 0.39 | 0.36 | 0.28 | 0.20 | 1 | 1 | 1 | 1 | 2 |
| | | CON4 | 0.16 | 0.12 | 0.13 | 0.15 | 0.18 | 4 | 4 | 4 | 4 | 4 |
| | | **CON5** | **0.06** | **0.00** | **0.00** | **0.02** | **0.09** | **6** | **6** | **6** | **6** | **6** |
| | | CON6 | 0.15 | 0.03 | 0.04 | 0.21 | 0.20 | 5 | 5 | 5 | 3 | 1 |

### H.9.1. Analysis of Proposed AHP with Conventional AHP

The benefits and aptness of proposed method (PAHP) as substitute of conventional methods (CAHP) is analyzed through the following analysis

1. Statistical analysis to evaluate the degrees of association between the proposed method (PAHP) and conventional methods (CAHP).
2. Assessment of PAHP in generating consistent pairwise judgments
3. Assessment of PAHP requiring less number of inputs.

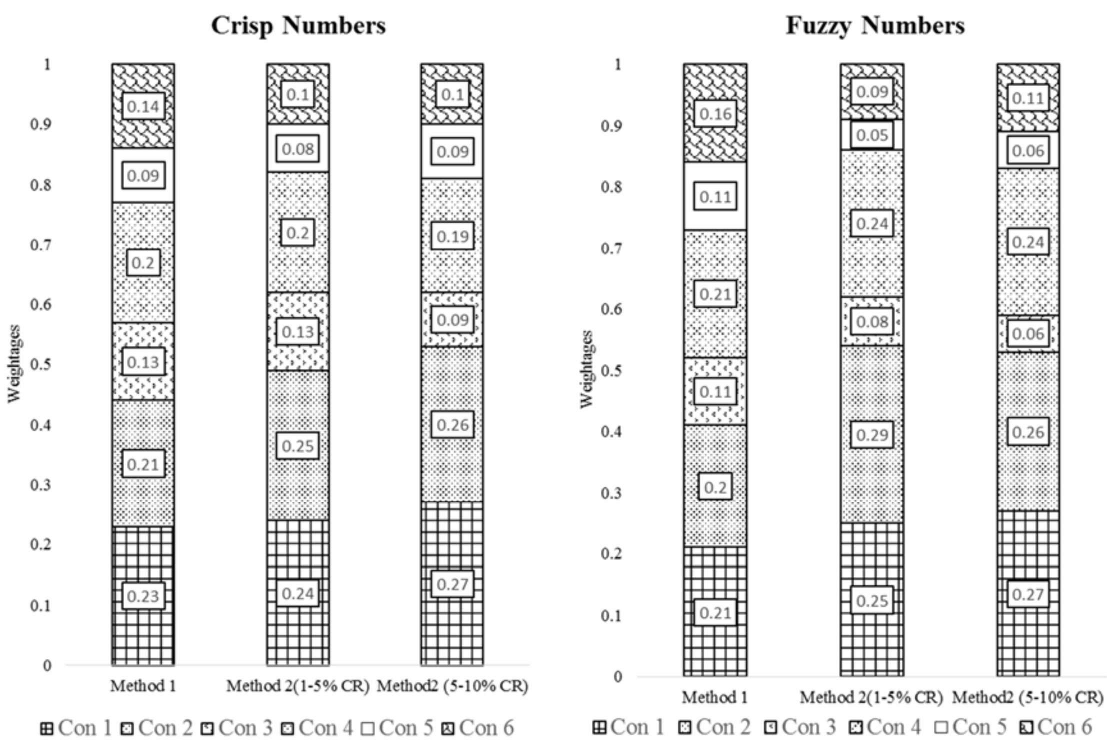


**Figure H.2 Comparison of Final Weightages (average of D1, D2, & D3) for each Contractor Calculated using PAHP and CAHP.**

### H.9.2. Statistical Analysis

Statistical analysis is performed by evaluating weightages generated because of the two approaches. Since parametric tests assume data to be normally distributed, it is proposed to use nonparametric tests which is not dependent on normal distribution of the data. Additionally, nonparametric tests are suited for small sample size and the nature of data (rank or ordinal). Even

in nonparametric tests, some tests compare means between two methods like Wilcoxon rank sum test, Kruskal Wallis test etc., which are not applicable for the present scenario as AHP is a relative comparison process. The Spearmen's Rank Order and Kendall Tau nonparametric tests were selected for correlation evaluation. Spearman's correlation coefficient (rs) measures the strength of association between two ranked variables. Kendall tau, τ, is similar to Spearman's method, however, it is better in discriminating between tied ranks. Also, Kendall's tau method is more suitable for smaller data sets (Field 2009).

Therefore, nonparametric tests Kendall Tau and Spearman Correlation were performed on the rankings (based on weightages) calculated by CAHP for crisp numbers for inputs given as per the proposed method and the CAHP method. Figure H.3 shows the correlation between the two methods using non-parametric tests. Tests were performed on the inputs given by three decision makers (D1, D2 and D3) and the results displayed are averages of three decision makers.

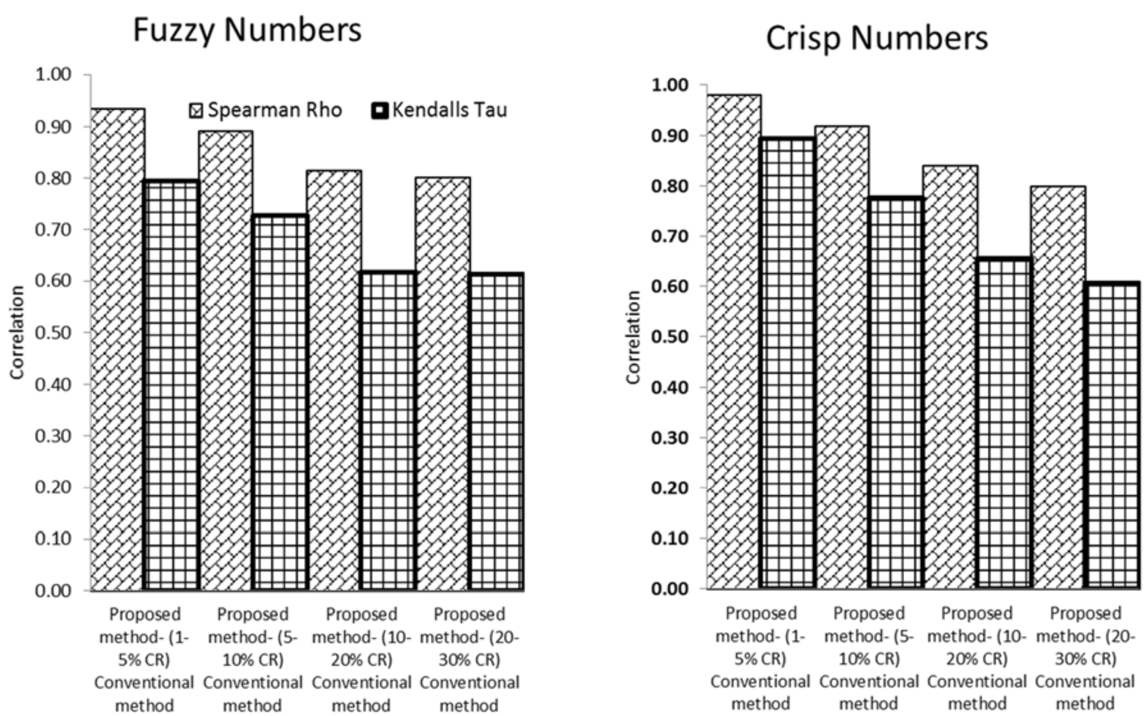


**Figure H.3 CAHP vs. PAHP Correlation Values for Pairwise Comparisons**

Positive correlations and similar trends were observed between the two methods (Figure 3). However, correlation values decreased with increasing consistency ratios. It was proposed by Saaty (1980) that the acceptable level of CR is 10% or less. A strong positive correlation 0.98 (spearman's rho) and 0.9 (Kendall tau) are observed between the two methods at 1-5% consistency ratio. As a value of 1 indicates perfect associativity between two methods, we can infer that PAHP and CAHP at lower consistency ratios are strongly associated.

In comparison to fuzzy numbers (Figure H.3a), the crisp numbers (Figure H.3b) resulted in higher correlation values. In Chang's extent analysis method, weightages are narrowed down i.e., sub-criteria with lower weightages are allotted a weightage of zero and added to higher weightages (Table H.4) resulting in increased weightage for CAHP. In the PAHP method, back calculation of the remaining pairwise comparisons using the additive transitivity property of fuzzy preference relations yielded pairwise comparisons which are not in the comparison scale as per Table H.1. Most of them are intermediate between the proposed scales of comparison. The PAHP generated weightages with less zero weightages whereas the CAHP method produced more zero weightages, resulting in lower correlation values. The problem may be alleviated by using intermediate values for the comparison scale in Chang's Extent analysis.

**H.9.3. Assessment of Consistency (comparison of CAHP and PAHP)**

In this section, the performance of PAHP and CAHP is compared more extensively. Achieving CR <0.1 is a challenge with increasing number of alternatives to compare. The main objective of this assessment was to examine the effectiveness of PAHP in generating required CR with increasing number of alternatives.

In order to estimate the efficiency of PAHP, a simulation analysis was performed using MATLAB. In this analysis, for developing decision matrices in simulations, the decisions were selected based on Tender Price. It was programmed in such a way that, in each simulation random Tender Prices were generated within the range of $850,000 to $1400, 000 (as per bid data in Table 2) for required number of alternatives. The pairwise comparisons were assigned based on the range

of difference between two contractors tender's price as shown in Table H.5 (lower price is valued more).

The analysis was demonstrated through an example. When six contractors were compared, the simulation generated the following costs.

$$\begin{bmatrix} \text{Contractor 1} \\ \text{Contractor 2} \\ \text{Contractor 3} \\ \text{Contractor 4} \\ \text{Contractor 5} \\ \text{Contractor 6} \end{bmatrix} = \begin{bmatrix} \$983{,}300 \\ \$1031{,}400 \\ \$903{,}900 \\ \$909{,}800 \\ \$1056{,}100 \\ \$872{,}400 \end{bmatrix}$$

The pairwise comparisons were performed based on this costs using Table H.5. The consistency is verified using the following methods.

**Table H.5 Pairwise Comparison Assignment for Comparing Contractors**

| Difference between Tender Price Contractors | Rating |
|---|---|
| \$0-\$10,000 | 1 |
| \$10,001-\$200,000 | 3 |
| \$200,001-\$400,000 | 5 |
| \$400,001-\$600,000 | 7 |
| >600,000 | 9 |

#### *H.9.3.1. PAHP Consistency Check*

The pairwise comparisons required for proposed methodology (n-1) were calculated based on the range explained in Table H.5. Based on the costs generated in the above example, the following decision matrix will be generated in the matrix.

The remaining inputs were calculated using the fuzzy preference relations using equations 7, 8 and 9. Once the decision matrix is completely calculated, the values are later converted into crisp numbers in the range of 1/9 to 9 and consistency ratio was calculated using equation 6.

$$\begin{pmatrix} & C1 & C2 & C3 & C4 & C5 & C6 \\ C1 & 1.00 & 3.00 & & & & \\ C2 & & 1.00 & 1/3 & & & \\ C3 & & & 1.00 & 1.00 & & \\ C4 & & & & 1.00 & 3.00 & \\ C5 & & & & & 1.00 & 1/3 \\ C6 & & & & & & 1.00 \end{pmatrix}$$

#### *H.9.3.2. CAHP Consistency Check*

CAHP needs more inputs than the PAHP, so the required inputs for CAHP were generated using two methods :

1. Generating all the required pairwise comparisons as per the range given in Table H.5.
2. Generating all the pairwise comparisons randomly from the set {9 7 5 3 1 1/3 1/5 1/7 1/9}.

The first method emulates the decision makers who make pairwise comparisons logically. Second method denotes that decision makers are not professional and make judgments inaccurately.

The following decision matrix was developed using the first method.

$$\begin{pmatrix} & C1 & C2 & C3 & C4 & C5 & C6 \\ C1 & 1.00 & 3.00 & 1/3 & 1/3 & 3.00 & 1/3 \\ C2 & & 1.00 & 1/3 & 1/3 & 3.00 & 1/3 \\ C3 & & & 1.00 & 1.00 & 3.00 & 1/3 \\ C4 & & & & 1.00 & 3.00 & 1/3 \\ C5 & & & & & 1.00 & 1/3 \\ C6 & & & & & & 1.00 \end{pmatrix}$$

Second method generated the following matrix

$$\begin{pmatrix} & C1 & C2 & C3 & C4 & C5 & C6 \\ C1 & 1.00 & 3 & 1/3 & 1/5 & 9 & 1/3 \\ C2 & & 1.00 & 1/3 & 1/3 & 3 & 1/3 \\ C3 & & & 1.00 & 1/3 & 3 & 1/7 \\ C4 & & & & 1.00 & 5 & 9 \\ C5 & & & & & 1.00 & 1/5 \\ C6 & & & & & & 1.00 \end{pmatrix}$$

The complete matrix was generated using reciprocal principle and CR was calculated using Equation 6. Overall, 20,000 iterations were performed by using different alternatives (3, 4, 5,…, 25) and verified consistency of PAHP and CAHP for every iteration. The summary of results were tabulated in Table H.6.

**Table H.6 Comparisons of CR of PAHP and CAHP of Randomly Generated Decision Matrix**

| No of Alternatives | PAHP | | | | CAHP | | | | CAHP (randomly generated) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Consistency Ratio | | | | Consistency Ratio | | | | Consistency Ratio | | | |
| | No of inputs required | 5 | 10 | 15 | No of inputs required | 5 | 10 | 15 | No of inputs required | 5 | 10 | 15 |
| 3 | 2 | 98 | 100 | 100 | 3 | 31 | 43 | 98 | 3 | 18 | 22 | 35 |
| 4 | 3 | 93 | 100 | 100 | 6 | 12 | 74 | 100 | 6 | 2 | 5 | 10 |
| 5 | 4 | 94 | 100 | 100 | 10 | 10 | 90 | 100 | 10 | 0 | 0 | 2 |
| 6 | 5 | 95 | 100 | 100 | 15 | 6 | 97 | 100 | 15 | 0 | 0 | 0 |
| 7 | 6 | 94 | 100 | 100 | 21 | 3 | 97 | 100 | 21 | 0 | 0 | 0 |
| 8 | 7 | 92 | 99 | 100 | 28 | 1 | 98 | 100 | 28 | 0 | 0 | 0 |
| 9 | 8 | 92 | 99 | 100 | 36 | 1 | 99 | 100 | 36 | 0 | 0 | 0 |
| 10 | 9 | 90 | 99 | 100 | 45 | 0 | 99 | 100 | 45 | 0 | 0 | 0 |
| 15 | 14 | 83 | 97 | 100 | 105 | 0 | 100 | 100 | 105 | 0 | 0 | 0 |
| 20 | 19 | 75 | 95 | 99 | 190 | 0 | 100 | 100 | 190 | 0 | 0 | 0 |
| 25 | 24 | 68 | 92 | 99 | 300 | 0 | 100 | 100 | 300 | 0 | 0 | 0 |

It is evident from the analysis that the PAHP is fulfilling the consistency requirement (CR <0.1 or 10%), when alternatives compared were less than eight and its performance was better even when the alternative increased up to twenty five.

CAHP using method 1 (where all pairwise comparisons were done logically) performed equally with PAHP. Although, CAHP using method 1 performed well, achieving CR with increasing number of alternatives is always demanding. Li et al.(2013) mentioned that when number of alternatives being compared are five or more, then achieving CR<0.1 is extremely difficult.

It can also be inferred from this case study that PAHP can comfortably generate decision matrices with CR 5-15% while CAHP is not able to achieve the same. Randomly generated pairwise comparisons failed to generate required CR.

Even though this case study shed some light on the efficiency of PAHP, it is really impractical to test consistency by assigning pseudo pairwise judgements through programming. In real life there will be subjectivity involved while assigning decision-making which cannot be captured by simulating the decision-making. The best way to compare the consistency between PAHP and CAHP is by comparing the real inputs from decision makers. Similar analysis was performed by Li et al. (2013) for testing the consistency of the AHP, they improved AHP by using a sorting and ranking methodology. They verified consistency up to seven alternatives only.

#### H.9.4. Assessment of PAHP Requiring Less Number of Pairwise Comparisons.

The main objective of this study is to reduce the number of pairwise comparisons and the following analysis shows the percentage of inputs reduced by the proposed method. The PAHP reduces the number of pairwise comparison compared with CAHP. Comparing n alternatives CAHP needs $\frac{n(n-1)}{2}$ pairwise comparisons and only $(n-1)$ for PAHP. The percentage decrease with pairwise comparisons is $\frac{(n-2)}{n} \times 100\ for\ n > 2$. Figure H.4 shows the decrease in the pairwise comparisons by PAHP. For example, if number of criteria to compare is ten then the proposed method reduces the number of comparisons by 80%. Higher the number of criteria to be compared higher the percentage of pairwise comparisons reduced by the proposed method.

### H.10. Conclusions and Future Study

Achieving less consistency ratio in CAHP is a tedious and complex process which can be simplified using the PAHP. The evaluation of results suggests that PAHP can be used instead of CAHP (both crisp and fuzzy numbers). Statistical analysis was performed to find the associativity of PAHP and CAHP on the rankings (based on weightages). Analysis revealed that a strong positive correlation 0.98 (spearman's rho) and 0.9 (Kendall tau) were observed between the two methods (PAHP vs CAHP) for 1-5% consistency ratio. Similar, trends were observed by comparing PAHP with FAHP using TFN instead of crisp numbers for pairwise comparison.

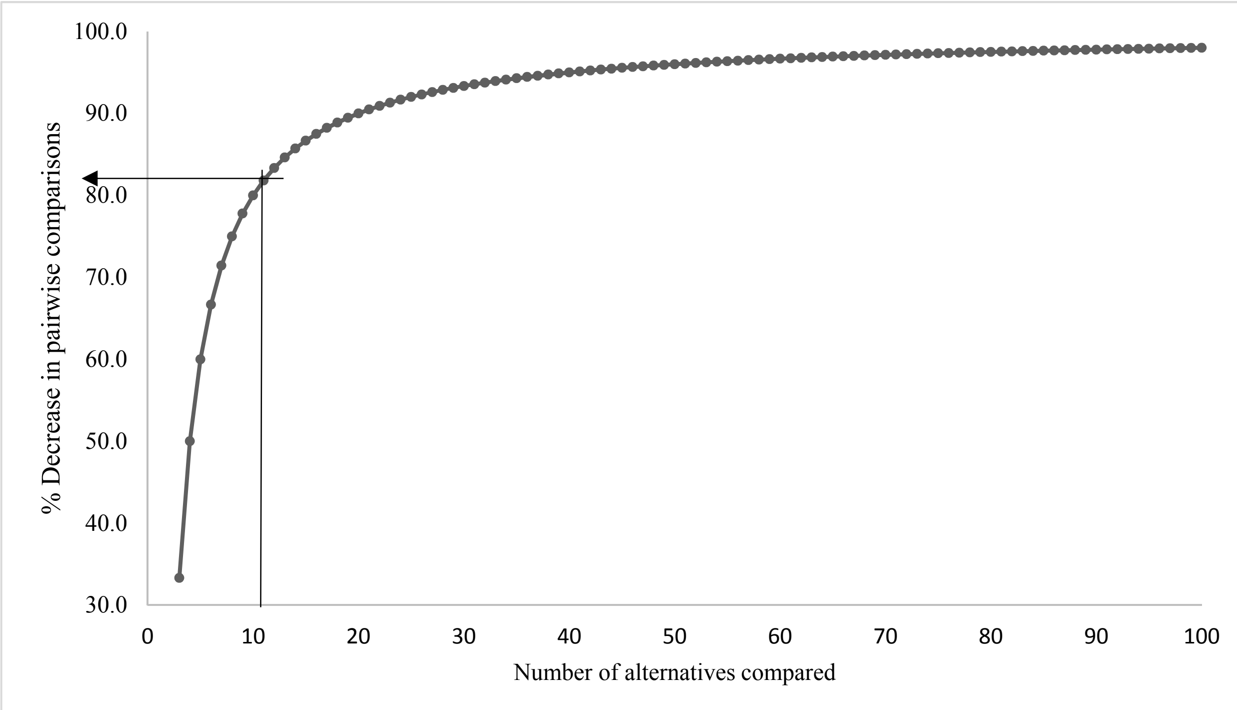


**Figure H.4 Percentage Decrease in Pairwise Comparisons by Proposed Method.**

The effectiveness of PAHP in generating consistent decision matrices was verified through simulations (20,000) with varying number of alternatives. The evaluation indicates that the PAHP performed reasonably well. However, more analysis is needed to validate the proposed approach. It is difficult to model consistency through simulation because it doesn't capture subjectivity involved in decision-making process. Further research is needed for analyzing PAHP consistency through input from numerous decision makers.

The PAHP reduces the number of pairwise comparisons significantly, and reduction is a function of number of alternatives being compared suggesting that the percentage of pairwise comparisons needed for analysis will be reduced with increase in number of alternatives being evaluated.

Further study is required to integrate group weightages using newer techniques rather than averaging of weightages (like Data Envelopment Analysis (DEA)) to better discriminate between

contractors or alternatives. Although not evaluated, the accuracy of pairwise comparisons provided by experts is vital for PAHP because remaining inputs will be generated from the provided inputs and needs to be evaluated.

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# Appendix I

The material of this appendix, is a technical manuscript entitled “Integration of Data Envelopment Analysis (DEA) based preference aggregation method and α-PSO (Particle Swarm Optimization) technique into group decision model” , was accepted for publication  to to the Journal of Computing in Civil Engineering ASCE.

# Appendix.I. Integration of Data Envelopment Analysis (DEA) Based Preference Aggregation Method and α-PSO (Particle Swarm Optimization) Technique into Group Decision Model

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## I.1. Abstract

The design of sustainable infrastructure is a complex process because it involves various fields of expertise such as engineering, economy, environment, social, etc. To make sure experts from various fields are part of decision-making, a heterogeneous group is typically formed and the individual decisions of the group are combined simply by using an arithmetic mean or geometric mean or by altering individual decisions to meet group consensus to generate a group decision. The drawbacks with these methods are inconsistency, dissatisfaction, and delayed decision process. This study proposes to use the Data Envelopment Analysis (DEA)-based preference aggregation method (commonly used by business community) to combine the individual inputs into group decision in conjunction with α constrained particle swarm optimization technique to generate consistent results in minimal time without altering individual decision-maker inputs. The proposed approach was evaluated by computing group decision weights for selection of a contractor out of six contractors with the help of nine decision-makers based on eight criteria using the Analytic Hierarchy Process (AHP). The results indicated that the proposed method was able to identify the most suitable contractor in minimal time without human intervention.

Key Words

Group decision-making, Data Envelopment Analysis (DEA), α Particle Swarm Optimization, Analytic Hierarchy Process.

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### I.2. Introduction

Increasing significance on building sustainable infrastructure has navigated the decision-making process to be a group decision. Typically, a heterogeneous (experts from different discipline) group is formed to embrace diverse views resulting in improved decisions (Srdjevic et al. 2013). The objective of experts in a group is to select the best alternative based on their expertise. Transforming individual decisions into group decisions is effortless if each member of the group is in full agreement with others, but seldom is this the case. Since group decisions are multi-factor and multi-actor, group decision-making becomes a fuzzy problem with high complexity, which is difficult to process. Over the years, various approaches like compromise, consensus, geometric mean aggregation, individual judgments, etc. (Srdjevic et al. 2013) have been proposed to minimize the complexity. Consensus can be defined as full agreement of all decision-makers regarding all the alternatives (Dong et al. 2010). Hence, earlier efforts were more focused on reaching consensus of the group which relieves the effort of combining individual decisions.

Mathematical models (Dong et al. 2010), (Chiclana et al. 2008) (Pérez et al. 2014) (Pedrycz and Song 2011) over the years have been developed to build consensus of individuals participating in group decision-making. In most of the methods, consensus is eventually achieved by manipulating the input of dissenting decision-maker(s) or by requesting the decision-maker(s), who have a difference of opinion, to modify their decision to meet the consensus. The modification of decision-maker inputs leads to dissatisfaction and nullifies the purpose of forming a heterogeneous group.

Another issue with group decision-making is aggregation of individual decisions. The simplest ways of combining individual decisions is either by the aggregation of individual judgments (AIJ) or by the aggregation of individual priorities (AIP). AIJ is accomplished by using the geometric mean while AIP is accomplished by the arithmetic mean. Escobar and Moreno-jiménez (2007) stated that both AIP and AIJ require precise judgments from decision-makers, which is unlikely in real life complex decision problems, and these methods ignore the

interdependencies between the different decision-makers. Recently, Alhumaidi (2014) proposed a group decision model for ranking contractors by using fuzzy weighted average method. The disadvantage with these methods is failure to generate a well-defined solution. Therefore, there is a need to develop a method for aggregating individual expert decisions into a group decision model without compromising the group decision process.

**I.3. Objective**

The objective of this study is to develop a method for aggregating individual decisions into a group decision for selection of the best alternative while minimizing the dissatisfaction of decision-makers. The main assumption of this study is that the decision-makers are knowledgeable, experienced, understand the problem at hand, and are expert.

**I.4. Approach**

To achieve this objective, understanding the tendency of each expert's decisions and clustering them with other experts is needed. There are many approaches for clustering expert's decisions, like data envelopment analysis, genetic algorithms, fuzzy sets, etc. Data envelopment analysis (DEA) is a useful assessment tool for solving problems with preference voting and aggregation (Wu et al. 2009). In this method, the efficiency score of each alternative is calculated based on how decision-makers evaluated that alternative, i.e., how that alternative is ranked compared to other alternatives and how much weightage is associated with the ranking. Each alternative is clustered based on rank i.e., how many decision-makers positioned that alternative in a rank, and next, the weightages assigned by each decision-maker to that alternative for achieving that rank are summed. This summation is then used in the linear programming model, which is subjected to some constraints for calculating the efficiency scores.

The most commonly used approaches have been proposed by AnGiZ et al. (2012) and Huang et.al (2009) . Both have proposed group decision models (GDM) that integrate the Analytic Hierarchy Process (AHP) with the DEA-based preferential aggregation method. The difference between the two methods is that AnGiZ et al. used the preferential weights and preferential ranks

of individual decision-makers for aggregating while Huang et al. used difference in preferential weights and preferential ranks for aggregating. Although the two models use different approaches, they typically yielded similar results (AnGiZ et al. 2012). Since AnGiZ's method of preferential ranks is the advanced version of Huang et al. method, AnGiZ's method of preferential ranks will be used in this study.

The linear programming model, proposed by AnGiZ, requires solving an optimization algorithm for calculating efficiency scores. The particle swarm optimization (PSO) technique, based on swarm intelligence, was selected to achieve the same because of its simplicity (Bai 2010) (Aziz et al. 2011) . The advantages of PSO include: simplistic approach, can be used for engineering, no need for overlapping and mutation calculation, and achieves optimization in a minimal time frame (Bai 2010). Although PSO was originally proposed for optimization of a single objective under unconstrained conditions, Takahama and Sakai (2004) modified PSO by including α constrained component in the approach. The optimization algorithm in this study always follows a particular trend which can be further applied to fine tune the αPSO such that the computational time is significantly reduced.

In summary, the AHP data were further massaged using the preferential rank method of DEA and is described in Section 1. The αPSO technique was then used for optimization and is described in Section 2. In Section 3, a case study is presented and the GDM process followed for contractor selection is also presented.

#### I.4.1. A. Section 1: Preferential Rank Method of Data Envelopment Analysis.

In multi-criteria decision-making, the experts scrutinize each alternative with respect to the defined criteria. Eventually they allocate weightages to all alternatives. When more than one expert is involved in decision-making, the crucial step is to aggregate each expert decision. Clustering according to the ranks assigned by each expert helps in understanding the overall tendency of the group. Occasionally, the ranks of all experts in the group will be the same; hence, there is also a need to include the weightages assigned to alternatives by experts in the analysis.

For example, assume a decision is required for selection of a product from three available products (A, B and C). To achieve this, four experts were asked to provide weightages to each product and the assigned weightages are shown in Table I.1. By clustering them into ranks, it is apparent that Product A is preferred thrice whereas B was preferred only once. However, keen observation on weightages reveals that A and B products are very close because the average weightages of A, B are (0.39, 0.40) and makes it difficult to decide on a product. On the basis of ranks, the Product A is the best; however, Product B is the best on the basis of summation of 'weightages'. In such situations, final judgment requires human intervention and may not yield consistent results. Further analysis of the data summarized in Table I.1 indicates presence of biasness of DM4 towards Product B, which skewed the results in favor of Product B. Thus, there is a need to have a system or process that is able to better discriminate between alternatives, requires minimal human intervention, and minimizes the influence of expert(s) biasness.

**Table I.1 Influence of Weightage on Selection of a Product**

| Decision Maker (DM) | Product | | |
|---|---|---|---|
| | A | B | C |
| 1 | 0.40 | 0.39 | 0.21 |
| 2 | 0.38 | 0.37 | 0.25 |
| 3 | 0.41 | 0.40 | 0.19 |
| 4 | 0.38 | 0.45 | 0.17 |

One such method is the Preferential Rank Method of Data Envelopment Analysis proposed by AnGiZ et al. which uses both the ranks achieved by each alternative and the weightages assigned to them. Based on ranks and weightages, the method calculates an efficiency score of alternatives and by normalizing the alternatives, final group weightages are determined. The steps to be followed, as per the AnGiZ et al. method, are summarized in Table I.2.

If weightages provided in Table I.1 are analyzed using the AnGiZ et al. method, the final weightages (Step 5 of Table I.2) of products (A, B, C) will be (0.54, 0.40, 0.06), which suggests that Product A should be selected. This method is better able to discriminate between alternatives and is able to minimize the influence of biasness of DM4 with minimal intervention.

**Table I.2 Methodology of Preferential Rank Method of Data Envelopment Analysis**

| Step | Description | Equation/ Matrix Symbol |
|---|---|---|
| 0 | The p number of decision-makers assigning weightages for assessing n alternatives. | $W = (w_{ij})_{p\times n}\; i = 1,2,\dots,p; j = 1,2,\dots,n$ <br> where $(w_{ij})$ is the decision weight of alternative j by decision-maker i. |
| 1 | Convert the weightages assigned to alternatives into a rank matrix R | $R = (r_{ij})_{p\times n}$ <br> where $r_{ij}$ is the ranking order of $w_{ij}$ in row $i$ of matrix $W$. |
| 2 | Using rank matrix R develop matrix S, which indicates how many times each alternative is placed in a particular rank. | $S = (s_{jk})_{n\times n}$ <br> where $s_{jk}$ indicates the number of times that alternative j is placed in rank k. |
| 3 | Develop matrix Ω, which denotes the summation of weightages of each alternative being in a rank. | $\Omega = (\Theta_{jk})_{n\times n}$ |
| 4 | Calculate the efficiency score of each alternative using modified Cook and Kress model (Cook.W.D. and Kress.M 1990). | $\begin{cases} max\beta_j = \sum_{k=1}^{n} u_k\Theta_{jk} \\ Subjected\ to \\ \sum_{k=1}^{n} u_k\Theta_{jk} \le 1\;\; j = 1,2,\dots,n \\ u_k - u_{k+1} \ge d(k,\mathcal{E})\quad k = 1,2,\dots,n-1 \\ u_n \ge d(k,\mathcal{E}) \\ d(k,\mathcal{E}), \mathcal{E} \ge 0, d(.,0) = 0 \end{cases}$ <br> where $d(k,\mathcal{E})$ is called the discrimination intensity function and Ɛ (error) is a number usually less than 1. |
| 5 | The group decisions weights are determined by normalizing the efficiency scores of each alternative | $w_j^G = \frac{\beta_j}{\sum_{i=1}^{n}\beta_i}$ <br> where $w_j^G$ indicates group weightage of alternative j, $\beta_j$ is the efficiency score of alternative j and n is the number of alternatives. |

Although the method is able to better discriminate, the effectiveness of the method becomes questionable with an increase in the number of alternatives and decision-makers because there is no standard discrimination function $d(k, \mathcal{E})$ and the error value is $\mathcal{E}$ provided (Cook and Kress 1990) , (Noguchi et al. 2002). Noguchi et al. performed extensive evaluation of efficiency score using the Cook and Kress model and proposed a new approach for calculating the efficiency score:

$$\begin{cases} max\beta_j = \sum_{k=1}^{n} u_k \, \Theta_{jk} \\ Subjected\ to \\ \sum_{k=1}^{n} u_k \Theta_{jk} \leq 1 \ \ j = 1,2,\dots,n \\ u_1 \geq 2u_2 \geq \cdots \geq nu_n \\ u_n \geq \mathcal{E} = \frac{2}{pn(n+1)} \end{cases} \quad (1)$$

The advantage of this approach is it eliminates the need of the discrimination function and also calculates the value of error ($\mathcal{E}$) based on number of alternatives in the decision-making process (Wu et al. 2009). Thus, it is proposed to use Noguchi's approach for calculating the efficiency score. Hence, Step 4 of Table I.2 is replaced with equation 1.

The group weightages are calculated by solving the equation of Step 5 (Table I.2) which is dependent on the efficiency score. With an increase in the number of alternatives, the efficiency score calculations become complex because the increase in the number of alternatives leads to increased number of constraints, rendering the efficiency score calculation complex. Hence, it is appropriate to use an optimization technique for calculation of the efficiency score. Although various optimization techniques are available (Awad et al. 2012), an α Constrained Particle Swarm Optimization (αPSO) is proposed to optimize the calculation of the efficiency score. An added advantage of this method is to integrate with DEA. The following section explains the αPSO method in detail.

### I.4.2. B. Section 2: α Constrained Particle Swarm Optimization (αPSO)

Since αPSO is a combination of PSO and the α Constrained Method, PSO is described first followed by the α Constrained Method.

#### *I.4.2.1. Particle Swarm Optimization*

PSO has been applied in various Civil Engineering applications by numerous researchers like Calibration of soil model parameters for Finite element modeling by Yazdi et al. (2011), analyzing pavement management activities (Tayebi et al. 2013), facility layout design optimization (Cheng and Lien 2012), rainfall runoff modeling (Asadnia et al. 2013), suspension bridge installation analysis (Chen et al. 2013), water distribution networks (Ezzeldin et al. 2013), construction operations (Zhang et al. 2006), water resources management (Baltar and Fontane 2008) etc. PSO can be better understood through an example. Let the objective or optimization problem be to solve the following equation:

$$Maximize\ A = x + y, subjected\ to\ 0 < x \leq 5\ and\ 0 < y \leq 15 \quad (2)$$

The solution for the above example is A=20. PSO randomly generates a set of initial solutions and the best solution in the group is identified. All the solutions modify their values based on the best solution in the group. In the next iteration, again the best solution in the modified values is identified and the other solutions change their positions based on the best solution in the group. In simple words, all the solutions try to follow the best solution in the group and also each particle memorizes their best position up to that iteration. Each solution is characterized by a position and a velocity. Each particle generated is assigned a position ($X_i$) and a velocity ($V_i$) where position represents a solution suggested by the particle, while velocity helps in changing the position of the particle based on the interactions of particles within the group. The interaction of particles depends on the best particle position ($g_{best}$) in the group in each iteration as well as the best position of the particle ($p_{best}$) up to that iteration.

As per PSO terminology, the number of initial solutions generated is called swarm size. For solving equation 2, let us consider a swarm size of 5. Each swarm is a set of (x, y) values and their velocities. The initial values of (x, y) and initial velocities are generated randomly and are included in Table I.3 as iteration 1.

**Table I.3 Swarm Positions Up To Five Iterations.**

| Iteration | Swarm | Particle Positions | | Velocities | | Objective Function | Particles Position |
|---|---|---|---|---|---|---|---|
| | | x | y | x | y | (x+y) | |
| 1 | 1 | 7.00 | 2.00 | 0.20 | 0.25 | 9.00 | $p_{best}$ |
| | 2 | 2.00 | 3.00 | 0.30 | 0.40 | 5.00 | $p_{best}$ |
| | 3 | 6.00 | 5.00 | 0.25 | 0.35 | 11.00 | $p_{best}$ |
| | 4 | 2.00 | 7.00 | 0.35 | 0.25 | 9.00 | $p_{best}$ |
| | **5** | **4.00** | **11.00** | **0.40** | **0.45** | **15.00** | $\mathbf{g_{best}}$ |
| 2 | 1 | 6.00 | 5.85 | -1.00 | 3.85 | 11.85 | $p_{best}$ |
| | 2 | 3.10 | 6.60 | 1.10 | 3.60 | 9.70 | $p_{best}$ |
| | 3 | 5.45 | 7.75 | -0.55 | 2.75 | 13.20 | $p_{best}$ |
| | 4 | 3.15 | 8.85 | 1.15 | 1.85 | 12.00 | $p_{best}$ |
| | **5** | **4.40** | **11.45** | **0.40** | **0.45** | **15.85** | $\mathbf{g_{best}}$ |
| 3 | 1 | 3.96 | 11.94 | -2.04 | 6.09 | 15.90 | $p_{best}$ |
| | **2** | **5.16** | **12.14** | **2.06** | **5.54** | **17.30** | $\mathbf{g_{best}}$ |
| | 3 | 4.26 | 11.98 | -1.19 | 4.23 | 16.24 | $p_{best}$ |
| | 4 | 5.26 | 11.74 | 2.11 | 2.89 | 17.00 | $p_{best}$ |
| | 5 | 4.96 | 11.90 | 0.56 | 0.45 | 16.86 | $p_{best}$ |
| 4 | 1 | 2.40 | 18.11 | -1.56 | 6.17 | 20.51 | $p_{best}$ |
| | **2** | **7.22** | **17.68** | **2.06** | **5.54** | **24.90** | $\mathbf{g_{best}}$ |
| | 3 | 3.43 | 16.27 | -0.83 | 4.29 | 19.70 | $p_{best}$ |
| | 4 | 7.33 | 14.79 | 2.07 | 3.05 | 22.12 | $p_{best}$ |
| | 5 | 5.60 | 12.45 | 0.64 | 0.55 | 18.05 | $p_{best}$ |
| 5 | 1 | 2.77 | 24.11 | 0.37 | 6.00 | 26.88 | $p_{best}$ |
| | **2** | **9.28** | **23.22** | **2.06** | **5.54** | **32.50** | $\mathbf{g_{best}}$ |
| | 3 | 4.12 | 21.13 | 0.69 | 4.86 | 25.25 | $p_{best}$ |
| | 4 | 9.36 | 19.00 | 2.03 | 4.21 | 28.35 | $p_{best}$ |
| | 5 | 6.89 | 15.09 | 1.29 | 2.64 | 21.97 | $p_{best}$ |

It is evident that swarm 5 generated the best solution (maximum value of (x+y) in the group). The particles update their positions and velocities based on the following equations 3 and 4.

$$v_i^{k+1} = wv_i^k + c_1 \times rand_1 \times (p_{best_i} - X_i) + c_2 \times rand_2 \times \left(g_{best_g} - X_i\right) \qquad (3)$$

where i is the particle's number (i=1…N; N: number of particles in the swarm),

$v_i^{k+1}$ Velocity of the particle for the next iteration $(k + 1)$,

$v_i^k$ Velocity of the particle for the current iteration (k),

w is the Inertia weight,

$c_1$ Self-confidence factor or cognitive factor,

$c_2$ Swarm confidence factor or social factor,

$X_i$ Position of particle for current iteration (k),

$p_{best_i}$ the best position of the particle till iteration (k),

$g_{best_g}$ Position of the best particle in the group for iteration (k), and

$rand_1$ & $rand_2$ are random numbers in the interval $[0, 1]$.

The equation 3 has three subparts: (1) the first subpart is called inertia which leads particles to move in the same direction, (2) second subpart is considered as 'personal influence' which helps swarm to improve its position compared to its current position, and (3) final subpart is known as 'social influence' which makes the swarm follow the best neighbor particle direction.

The updated position of particle $X_i^{k+1}$ can be computed using the following equation 4

$$X_i^{k+1} = X_i^k + v_i^{k+1} \tag{4}$$

The following are the parameters considered for calculation: $c_1 = 2.0, c_2 = 2.0$, w=1.0 and rand1=0.1 and rand2=0.2. For easiness rand1 and rand2 values are considered in this example, but in reality they are random variables which change with iterations.

The results from five iterations employing equation 3 & 4 and using the above parameters are shown in Table I.3. It is evident that the particles are updating their positions and the value of (x+y) is increasing with each iteration.

Even though PSO is a simple optimization technique, it is not applicable in a constrained environment. For instance, 5 gbest (for iteration 5) swarm has (x,y) as (9.28, 23.22) but the particles (x,y) are ignoring $0 < x \leq 5 \; and \; 0 < y \leq 15$ are ignoring the constraints. Thus, researchers have evolved PSO over the years to handle optimization problems consisting of multi objectives under constrained conditions. In general, evolutionary algorithm optimization methods for constrained problems can be categorized into four methods namely: 1) Preserve feasibility of

solutions, 2) Penalty functions, 3) Differentiate the feasible and infeasible solutions, and 4) Hybrid Method (Michalewicz and Schoenauer 1996). Briefly, in the feasibility method, the particles which satisfy the constraints are preserved for optimization. This method needs to generate a huge swarm to satisfy constraints. The penalty function method is one of the widely used methods in which the constrained problem is modified into an unconstrained problem by altering the objective function and by adding some penalties. The third method differentiates the feasible and infeasible solutions i.e., feasible solutions are the swarm which satisfies the constraints and unfeasible solutions are those which failed to satisfy the constraints. This method attempts to transform unfeasible solutions into feasible solutions. In the hybrid method, a combination of any two or more different methods are used.

A new constrained optimization method αPSO is proposed by Takahama and Sakai (2004) which is a combination of the α constrained method and PSO. It is a special transformation function, which maintains the objective function. The particle, which satisfies the constraints, will proceed to optimize the objective function and the particle, which does not satisfy the constraints, is modified such that it satisfies the constraints (Third Method). The following section describes the α constrained method.

#### *I.4.2.2. The α Constrained Method*

This method consists of two vital steps, namely satisfaction level calculation (it is different from decision-makers satisfaction level as discussed previously) and α level comparison which can be employed in handling constraints. In the satisfaction level step, one can verify whether the particle satisfies the constraint. If satisfaction level $\mu(x)$ equals to 1 then particle satisfies the constraint, otherwise, the satisfaction level will be $0 \leq \mu(x) \leq 1$ which means particle doesn't satisfies the constraint.

The second step is α level comparison in which particles are compared based on the satisfaction levels and the objective function values of the particles. This assists PSO in identifying

$p_{best}$ and $g_{best}$ particles. The particles which have a better satisfaction level are considered superior than other particles irrespective of the optimization function value.

Table I.4a shows the satisfaction level calculation procedure and it also includes the calculation of the example problem as shown in equation 2. The Table 4a also shows the calculation for the first two particles used in the PSO method which uses same particles that were used in the explanation of PSO method. The α level comparison method is explained through Table I.4b. In addition to these tables, the first three iterations of α Constrained PSO are shown in Table I.5. Closer examination of these iterations reveals that the primary importance of the optimization is satisfying the constraints followed by optimization. The objective function (x+y) of individual swarm is less than 20 as well as x and y values are within constraints of 5 and 15, respectively. Additionally, objective function value at the end of iteration 3 is similar (16.30 to 16.86) for all swarms and all of the particles achieved a satisfaction of level of 1 indicating that the proposed approach is able to achieve desired satisfaction score with minimal iterations by satisfying specified constrains.

**Table I.4 a : Satisfaction Level $\mu(x)$ Calculations, α Level Comparison Calculations**

I.4.a

| Description | Problem/Equation | Example | Remarks |
|---|---|---|---|
| If optimization problem is to maximize a function with two constraints. | $\begin{cases} maximize\ f(x) \\ subjected\ to \\ g_j(x) \leq 1, \quad j = 1,2,\ldots,q \\ h_j(x) \geq 0, j = 1,2,\ldots,q \end{cases}$ | $\begin{cases} maximize\ A = x + y \\ subjected\ to \\ 0 < x \leq 5 \\ 0 < y \leq 15 \end{cases}$ | Particle 1 $(x_1,y_1)$=(7.00,2.00) Particle 2 $(x_2,y_2)$=(2.00,3.00) Values taken from the example above |
| If the particle satisfies all constraints then $\mu(x)=1$ otherwise $0 \leq \mu(x) \leq 1$. | $\begin{cases} \mu(x) = 1, \text{if } g_j(x) \leq 1, \\ h_j(x) \geq 0 \text{ for all j} \\ 0 \leq \mu(x) \leq 1, \quad \text{otherwise} \end{cases}$ | Satisfaction level Particle 1 (x1,y1)=(<1,1) Particle 2 (x2,y2)=(1,1) | The value of x1 is outside the limits so satisfaction level is less than 1. |
| Calculate the satisfaction level of particles that failed to satisfy constraints. | $\mu_{gj}(x) = \begin{cases} 1, if\ g_j(x) \leq 1 \\ 1 - \frac{\lvert g_j(x)\rvert}{b_1} \end{cases}$ <br> $\mu_{hj}(x) = \begin{cases} 1, if\ h_j(x) \geq 0 \\ 1 - \frac{\lvert h_j(x)\rvert}{b_2} \end{cases}$ | $\mu_1\ (x_1) = 1 - \left\lvert\frac{7}{50}\right\rvert$=0.86 <br> $\mu_1\ (x_{1,}y_1) = (0.86,1)$. <br> $\mu_2\ (x_{2,}y_2) = (1,1)$. | $b_1$ and $b_2$ are proper positive real numbers. The values b1 and b2 depends on the constraint values of $g_j(x)$ and $h_j(x)$. |
| The final satisfaction level of a particle. | $\mu(x) = \min\{\mu_{gj}(x), \mu_{hj}(x)\}$ | $\mu(1) = \min\{0.86,1\} = 0.86$ <br> $\mu(2) = \min\{1,1\} = 1$ | In particle 1 $x_1$ fails to satisfy even though $y_1$ satisfies, so the overall satisfaction level is less than 1. |

I.4 b

| | | | |
|---|---|---|---|
| For any α satisfying $0 \leq \alpha \leq 1$, α level comparison $>_\alpha$ and $\geq_\alpha$ between $(f_1, \mu_1)$ and $(f_2, \mu_2)$ | $(f_1, \mu_1) >_\alpha (f_2, \mu_2)$ $\Leftrightarrow \begin{cases} f_1 > f_2, if\ \mu_1, \mu_2 \geq \alpha \\ f_1 > f_2, if\ \mu_1 = \mu_2 \\ \mu_1 > \mu_2, otherwise \end{cases}$ | Even though the function value of particle1 is higher than particle2. This comparison considers particle 2 is superior than 1 because it has higher satisfaction level. | f=x+y, $(f_1, \mu_1) = (7 + 2{,}0.86)$=(9,0.86) $(f_2, \mu_2) = (2 + 3{,}1.00)$= (5,1). The value of α can be from $0 \leq \alpha \leq 1$. For this example value of 1 is considered. |

**Table I.5 First Three Iterations of α Constrained PSO**

| Iteration | Swarm | Particle Position | | Objective Function (x+y) | Updated Velocities | | Satisfaction level | | Total Satisfaction level | Particle Status |
|---|---|---|---|---|---|---|---|---|---|---|
| | | x | y | | x | y | x | y | | |
| 1 | 1 | 7.00 | 2.00 | 9.00 | 0.20 | 0.25 | 0.86 | 1.00 | 0.86 | $p_{best}$ |
| | 2 | 2.00 | 3.00 | 5.00 | 0.30 | 0.40 | 1.00 | 1.00 | 1.00 | $p_{best}$ |
| | 3 | 6.00 | 5.00 | 11.00 | 0.25 | 0.35 | 0.88 | 1.00 | 0.88 | $p_{best}$ |
| | 4 | 2.00 | 7.00 | 9.00 | 0.35 | 0.25 | 1.00 | 1.00 | 1.00 | $p_{best}$ |
| | **5** | **4.00** | **11.00** | **15.00** | **0.40** | **0.45** | **1.00** | **1.00** | **1.00** | $\mathbf{g_{best}}$ |
| 2 | 1 | 6.00 | 5.85 | 11.85 | -1.00 | 3.85 | 0.88 | 1.00 | 0.88 | $p_{best}$ |
| | 2 | 3.10 | 6.60 | 9.70 | 1.10 | 3.60 | 1.00 | 1.00 | 1.00 | $p_{best}$ |
| | 3 | 5.45 | 7.75 | 13.20 | -0.55 | 2.75 | 0.89 | 1.00 | 0.89 | $p_{best}$ |
| | 4 | 3.15 | 8.85 | 12.00 | 1.15 | 1.85 | 1.00 | 1.00 | 1.00 | $p_{best}$ |
| | **5** | **4.40** | **11.45** | **15.85** | **0.40** | **0.45** | **1.00** | **1.00** | **1.00** | $\mathbf{g_{best}}$ |
| 3 | 1 | 4.36 | 11.94 | 16.30 | -1.64 | 6.09 | 1.00 | 1.00 | 1.00 | $p_{best}$ |
| | **2** | **4.72** | **12.14** | **16.86** | **1.62** | **5.54** | **1.00** | **1.00** | **1.00** | $\mathbf{g_{best}}$ |
| | 3 | 4.48 | 11.98 | 16.46 | -0.97 | 4.23 | 1.00 | 1.00 | 1.00 | $p_{best}$ |
| | 4 | 4.80 | 11.74 | 16.54 | 1.65 | 2.89 | 1.00 | 1.00 | 1.00 | $p_{best}$ |
| | 5 | 4.80 | 11.90 | 16.70 | 0.40 | 0.45 | 1.00 | 1.00 | 1.00 | $p_{best}$ |

#### I.4.3. C. Section 3: Group Decision Model (GDM)

As discussed previously, clustering of individual decisions is the key in the preference aggregation method of data envelopment analysis (clustering of individual decisions with respect to rank and weightage allotted to each alternative by each decision-maker). The proposed model uses linear programming for maximizing the satisfaction of decision-makers in calculating the efficiency score of each alternative and later, this efficiency score is used in calculating the group weightages. Although various commercial software/tools are available for solving linear programming models, they cannot be embedded in DEA and is required in the present study. Based on studying various optimization algorithms, particle swarm optimization (PSO) was identified to be a suitable algorithm because of ease in integration with DEA and coding.

The main drawback of PSO is its inability to handle multiple constraints and often this surmounts the advantages of PSO. To overcome the drawback, PSO is enhanced with α constrained

method. The initial swarm generated randomly in PSO can be produced in a way that they follow the trend of constraints in the efficiency score model. This further increases the probability of swarm having particles which satisfies the constraints in a minimal number of iterations. This is similar to the first method (feasible solution) explained previously in handling constraints, however, instead of a complete feasible solution, the proposed method generates a partial feasible solution. The benefits of this partial feasible solution are illuminated better through a case study explained in a later section (Results and Discussion). Hence, the proposed method for handling constraints can be considered as a hybrid method as it combines the two methods.

Figure I.1 presents the cross functional flowchart of the proposed GDM. The first column represents the steps involved in the preference aggregation method, the second column designates the particle swarm optimization and the third column describes the α-constrained method. The proposed model is used for selecting a contractor from six contractors based on the decisions from nine experts.

#### I.4.4. D. Section 3: Case Study: Selection of a Contractor from Six Contractors based on Decisions from Nine Experts.

The proposed method is evaluated by fabricating a case study and selecting a suitable contractor with the help of nine decision makers. A fabricated case study was performed in which bids submitted by six contractors (as shown in Table I.6) were given to nine experts to assign pairwise comparisons to contractors based on four criteria and six sub criteria (Figure I.2). The assigned comparisons were then converted into weightages based on the Analytic Hierarchy Process (AHP). It is a multi-criteria decision model, which is being used in infrastructure building. It combines both tangible and intangible criteria and is widely used as a multi-criteria tool in GDM. The proposed methodology for group weightages is applicable in other decision tools as well.

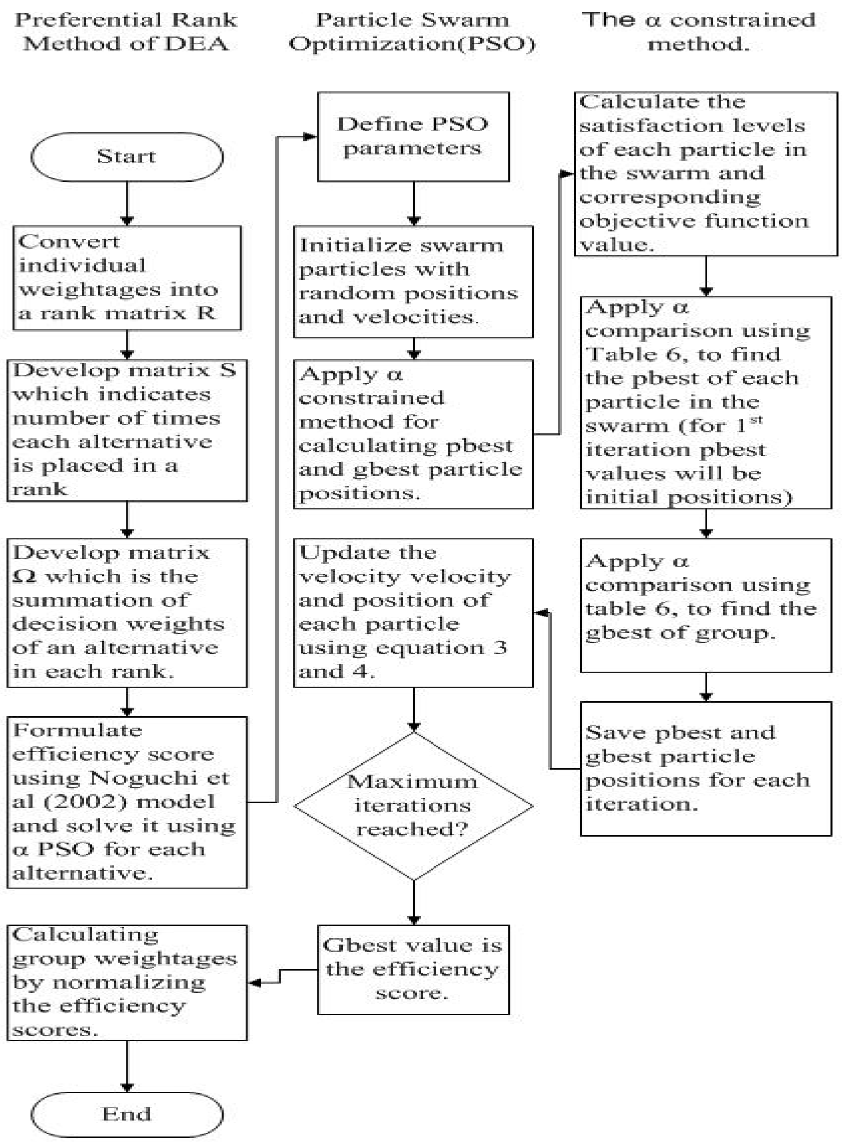



**Figure I.1 Cross Functional Flowchart of Preferential Rank Method of Data Envelopment Analysis, Particle Swarm Optimization and α Constrained Method**

**Table I.6 Bid Data**

| Contractor | Tender Price | Failure to complete contracts | Financial Stability & references | Cost overruns | Quality | Safety | Experience in local area | Scale of Projects Completed |
|---|---|---|---|---|---|---|---|---|
| 1 | $916,672 | 19 | Very Good | 18 | Excellent | Excellent | 5 | 4 |
| 2 | $1,399,771 | 8 | Excellent | 8 | Excellent | Excellent | 6 | 6 |
| 3 | $1,342,415 | 21 | Fair | 32 | Fair | Excellent-Good | 18 | 14 |
| 4 | $931,980 | 17 | Very good | 38 | Excellent-good | Fair-Poor | 5 | 4 |
| 5 | $854,540 | 15 | Fair-Poor | 38 | Fair | Poor | 1 | 1 |
| 6 | $1,154,620 | 16 | Poor | 40 | Good-Fair | Good | 5 | 4 |

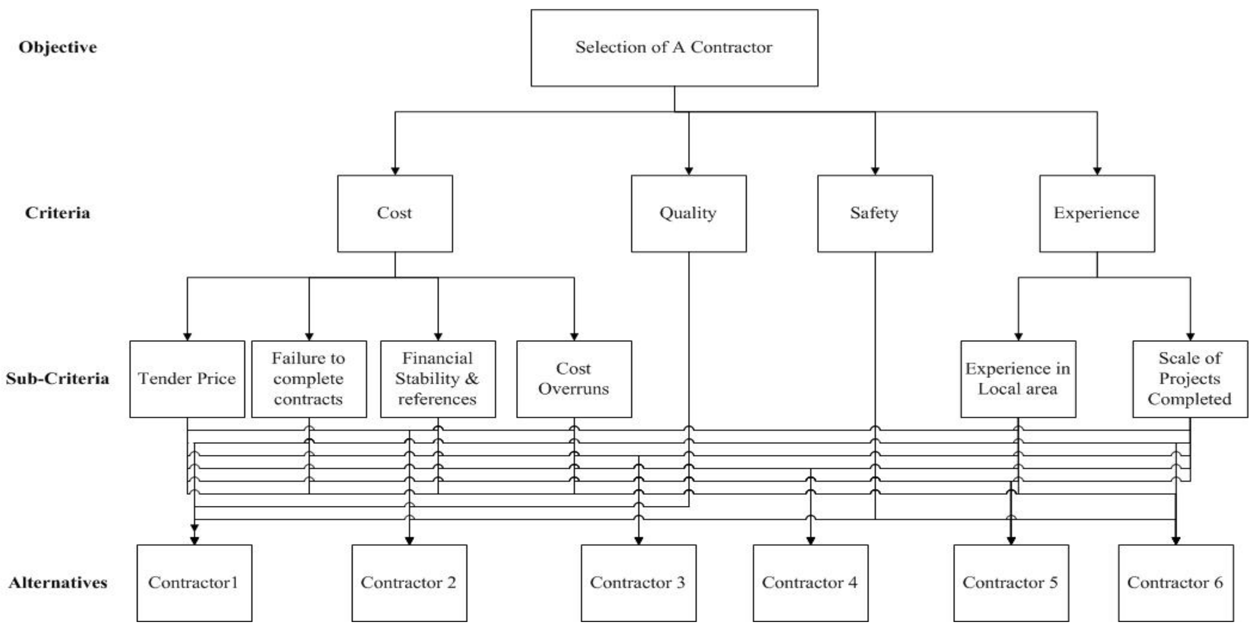



**Figure I.2 Hierarchy Tree and Contractor Selection Criteria**

Since AHP theory suggests that the consistency index (consistency of individual decision-makers) needs to be less than 10% (Forman 1990), the consistency index was verified at all levels. The final weightages assigned for each contractor by nine decision-makers are shown in Figure I.3 and the rankings of contractors based on weightages are shown in Figure I.4. The data summarized in Figure I.4 suggests that decision-makers, in general, favored either Contractor One or Contractor

Two while some of the decision-makers were in favor of Contractor Four as well. On the flip side, decision-makers were definitely not in favor of Contractors Three, Five, and Six. Occasionally, the calculated weightages were similar. For instance, Decision Makers 7 and 9 weightages were similar for Contractor One and Two.

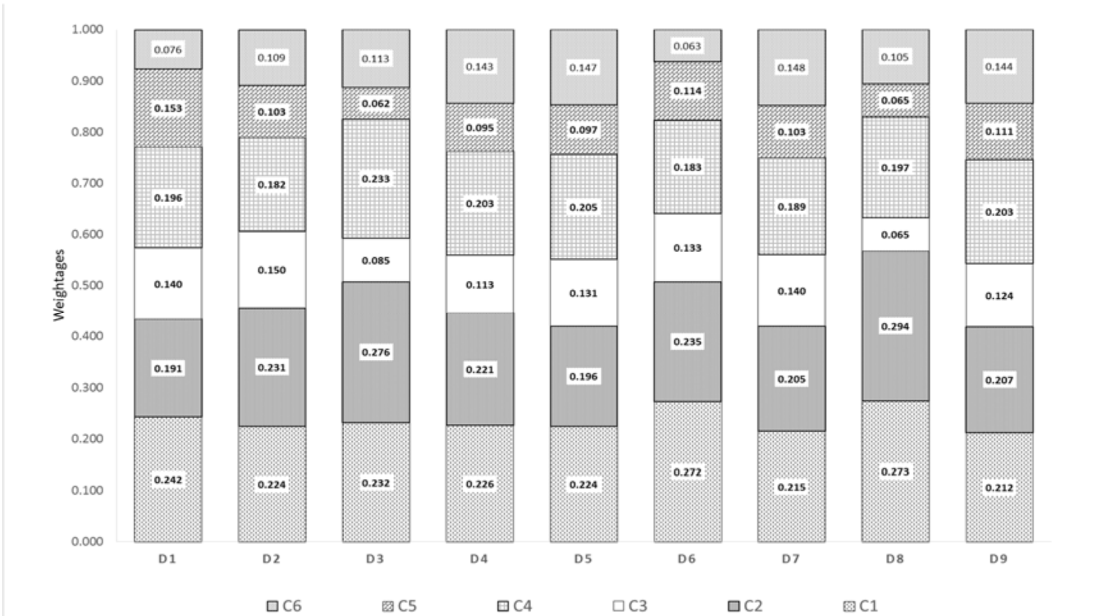



**Figure I.3 Weightages Calculated using AHP**

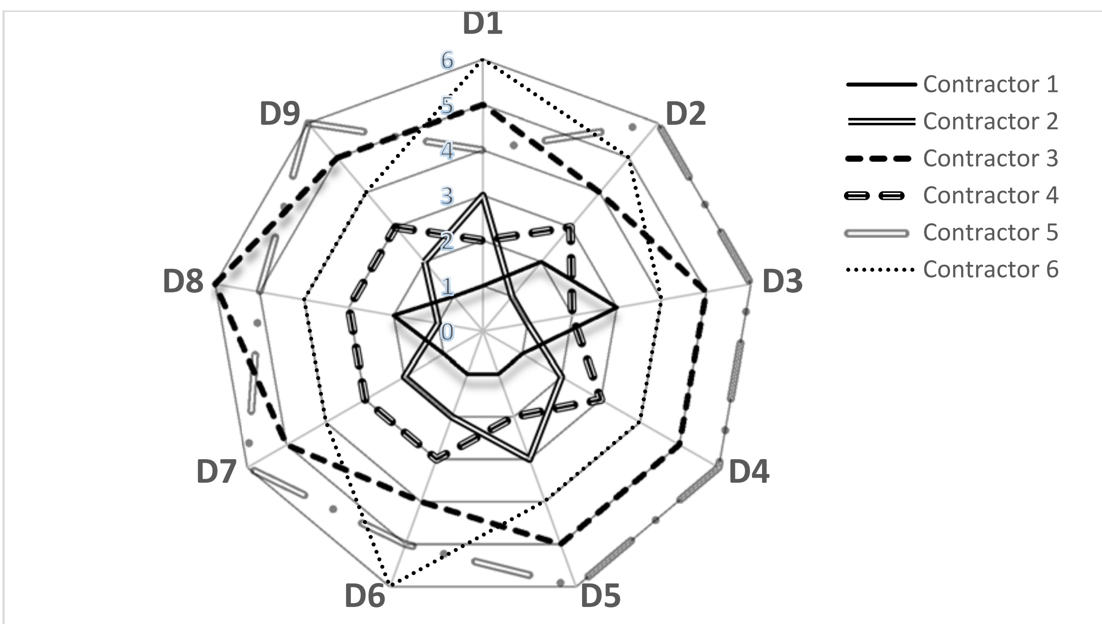



**Figure I.4 Individual Contractor Rankings**

To explain aggregating, the weightages calculated for four criteria, namely, cost, quality, safety and experience based on individual decision-maker's preference along with their respective ranks (rank matrix R) are summarized in Table I.7a. The data indicates that most of the decision-makers ranked contractors based on cost. In addition, some of the decision-makers ranked cost as well as quality as the important factor. The decision-makers were then clustered according to their preference based on calculated ranking. For instance, eight decision-makers ranked cost as number one while three decision-makers ranked quality as the number one criterion. Similarly, six decision-makers ranked safety as number four. The calculated weightages were then summed as per the rank and criteria shown in Table I.7 b. In other words, the weightages calculated for cost from input provided by eight decision-makers (who ranked cost to be number one) were added and included in Table I.7b. Since none of the decision-makers ranked cost higher than two, the summation of weightages is zero in R3 and R4. The Matrix Ω is calculated by adding weightages assigned by individual decision makers with similar rankings.

**Table I.7 a) Weightages and Ranks Assigned to Each Criteria, b) Matrix S (Number of Times Each Criterion is Placed in a Rank) & Matrix Ω (Summation of Decisions Weights of Each Criterion in Each Rank)**

| **A:** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Decision Maker | Weightages | | | | Rank matrix R | | | |
| | Cost | Quality | Safety | Experience | Cost | Quality | Safety | Experience |
| 1 | 0.526 | 0.217 | 0.04 | 0.217 | 1 | 2 | 4 | 2 |
| 2 | 0.526 | 0.217 | 0.04 | 0.217 | 1 | 2 | 4 | 2 |
| 3 | 0.438 | 0.438 | 0.063 | 0.063 | 1 | 1 | 3 | 3 |
| 4 | 0.388 | 0.388 | 0.112 | 0.112 | 1 | 1 | 3 | 3 |
| 5 | 0.406 | 0.271 | 0.053 | 0.271 | 1 | 2 | 4 | 2 |
| 6 | 0.567 | 0.207 | 0.039 | 0.187 | 1 | 2 | 4 | 3 |
| 7 | 0.414 | 0.25 | 0.039 | 0.297 | 1 | 3 | 4 | 2 |
| 8 | 0.427 | 0.455 | 0.061 | 0.058 | 2 | 1 | 3 | 4 |
| 9 | 0.462 | 0.33 | 0.05 | 0.158 | 1 | 2 | 4 | 3 |
| **B :** | | | | | | | | |
| Criteria | Matrix S (No of times each criterion is placed in a rank) | | | | Matrix Ω (Summation of decision weights of each criterion in each rank) | | | |
| | Rank1 | Rank2 | Rank3 | Rank4 | Rank1 | Rank2 | Rank3 | Rank4 |
| Cost | 8 | 1 | 0 | 0 | 3.727 | 0.427 | 0 | 0 |
| Quality | 3 | 5 | 1 | 0 | 1.281 | 1.242 | 0.25 | 0 |
| Safety | 0 | 0 | 3 | 6 | 0 | 0 | 0.236 | 0.261 |
| Experience | 0 | 4 | 4 | 1 | 0 | 1.002 | 0.52 | 0.058 |

The DEA model proposed by Noguchi et al. (2002) is used to find the efficiency score. As per equation 1, the efficiency score for cost was achieved by maximizing the following equation:

$$\begin{cases} eff_{cost}\ \max 3.727u_1 + 0.427u_2 + 0.000u_3 + 0.000u_4 \\ \quad\quad\quad Subjected\ to \\ 3.727u_1 + 0.427u_2 + 0.000u_3 + 0.000u_4 \leq 1 \\ 1.281u_1 + 1.242u_2 + 0.250u_3 + 0.000u_4 \leq 1 \\ 0.000u_1 + 0.000u_2 + 0.236u_3 + 0.261u_4 \leq 1 \\ 0.000u_1 + 1.002u_2 + 0.520u_3 + 0.058u_4 \leq 1 \\ u_1 \geq 2u_2 \geq 3u_3 \geq 4u_4 \\ u_4 \geq \mathcal{E} = \frac{2}{pn(n+1)} = \frac{2}{9\times4\times(5)} = 0.011 \end{cases} \tag{5}$$

Similarly, the efficiency score for quality, safety and experience can be calculated by solving the following equations 6, 7 & 8, with the constraints the same as mentioned in equation 5.

$$eff_{quality}\ \ max\, 1.281u_1 + 1.242u_2 + 0.250u_3 + 0.000u_4 \tag{6}$$

$$eff_{safety}\ \ max\, 0.000u_1 + 0.000u_2 + 0.236u_3 + 0.261u_4 \tag{7}$$

$$eff_{experience}\ \ \max 0.000u_1 + 1.002u_2 + 0.520u_3 + 0.058u_4 \tag{8}$$

Equation 5 is optimized by using PSO combined with the α-constrained method explained in section 2. The following are the parameters considered in optimization: swarm size of 25, no. of iterations 1,000, $c_1 = 2.0, c_2 = 2.0, b_1 = 75,\ b_2 = 75$, w=1.0 and α=1.0. Typically, the values of c1 and c2 are considered as 2 and w is equal to 1 (Bai 2010). Swarm size of 25 implies, 25 sets of $u_1$,$u_2$, $u_3$ and $u_4$ random variables and their velocities. The objective function value for each set of particles will be calculated and the constraints will be verified. The best swarm set is the one which satisfies all of the constraints (or most of them) and will have the maximum objective value. All of the remaining swarm sets will adjust their values based on the best set.

The constrained function values in the present case study in equation 5 are less than 10 and higher values of b1 & b2 will lead to values closer to 1 i.e., even if constraints are failed, the value 1 indicates constraints are satisfied. So values of 75 are considered in this study. In the α constrained method, the value of α=1 is considered but the results were verified at various values

of α like 0.9, 0.8, 0.7 etc. At all values of α, efficiency scores remained the same but the code running time increased at lower α values.

### I.5. Results and Discussions

Although α-PSO can solve equation 5, its efficiency is questionable with an increase in problem complexity. The efficiency score as defined in equation 1 has constraints which are a function of the number of alternatives being compared in decision-making. Equation 5 outlines the mathematical model (objective function) for calculating the efficiency score for the 'cost' criterion and it has six constraints. Here, four criteria i.e., cost, quality, safety and experience were appraised by each decision-maker and the group aggregating model has six constraints. If there were five criteria involved, then the aggregating model would have seven constraints instead of six. The more number of constraints necessitates more iterations in α-PSO or large swarm size, which increases the computational time. For example, to evaluate the group aggregate weight for contractor 1 pertaining to sub criteria 'tender price', it is necessary to calculate the efficiency score as per the procedure explained above. The efficiency score for a contractor is expressed in equation 9.

$$\begin{cases} eff_{c1\_tender} \quad max\ 1.327u_1 + 1.047u_2 + 0.2260u_3 + 0.000u_4 + 0.000u_5 + 0.000u_6 \\ \text{Subjected to} \\ 1.327u_1 + 1.047u_2 + 0.2260u_3 + 0.000u_4 + 0.000u_5 + 0.000u_6 \leq 1 \\ 0.000u_1 + 0.000u_2 + 0.000u_3 + 0.3440u_4 + 0.3470u_5 + 0.000u_6 \leq 1 \\ 0.000u_1 + 0.000u_2 + 0.000u_3 + 0.000u_4 + 0.030u_5 + 0.270u_6 \leq 1 \\ 0.000u_1 + 0.871u_2 + 0.983u_3 + 0.000u_4 + 0.000u_5 + 0.000u_6 \leq 1 \\ 1.816u_1 + 0.916u_2 + 0.000u_3 + 0.000u_4 + 0.000u_5 + 0.000u_6 \leq 1 \\ 0.000u_1 + 0.000u_2 + 0.000u_3 + 0.590u_4 + 0.237u_5 + 0.000u_6 \leq 1 \\ u_1 \geq 2u_2 \geq 3u_3 \geq 4u_4 \geq 5u_5 \geq 6u_6 \\ u_6 \geq \varepsilon = \frac{2}{pn(n+1)} = \frac{2}{9\times6\times(7)} = 0.005 \end{cases} \tag{9}$$

The above equation 9 was evaluated by α-PSO using various swarm sizes like 15,20,25,30 etc. At lower swarm sizes (<25), even after 1,000 iterations, α-PSO did not yield the best solution i.e., swarm failed to satisfy all constraints (satisfaction level less than 1). Figure I.5 shows the computation with a swarm size of 25 using α-PSO. At 400 iterations, only some swarm particles satisfied all constraints and reached solution 0.85 (solution for Equation 9). Even after 1,000

iterations, still some other swarm failed to satisfy the constraints. Even though it is not mandatory in PSO that all swarm should be at the same solution by the end of desired number of iterations, the scattered swarm is an indication of inefficiency of the method and more computational time.

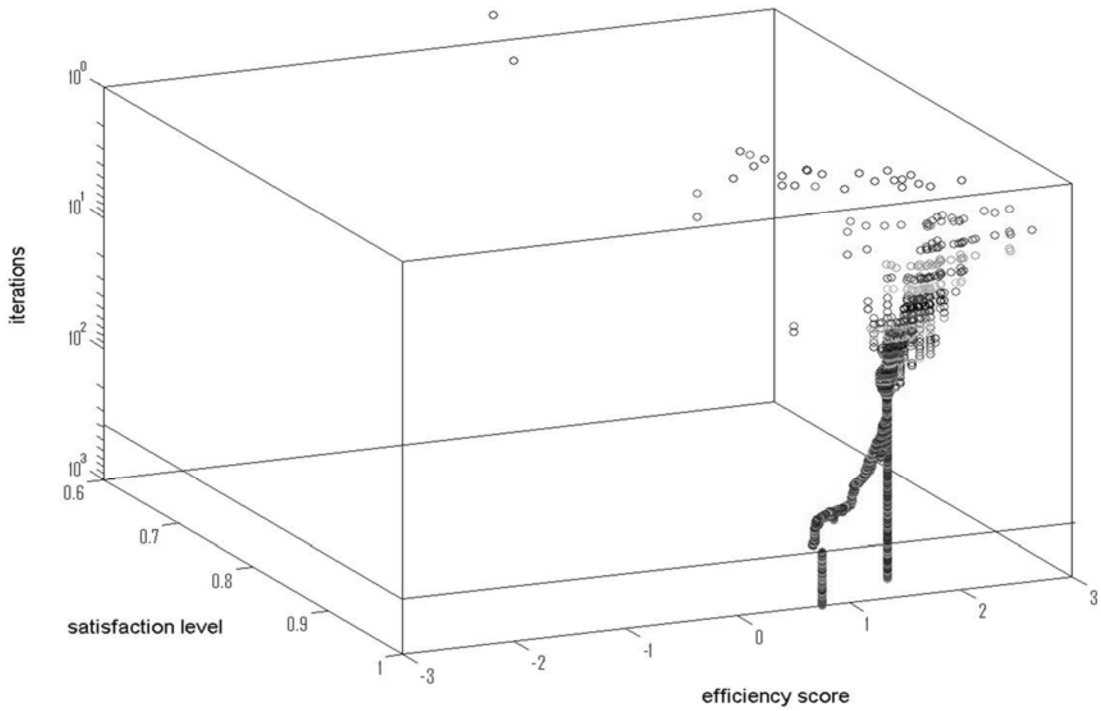



**Figure I.5 Efficiency Score for Contractor 1 Pertaining to 'Tender Price' using α-PSO**

In this study, a hybrid approach is proposed which combines α-PSO with a partial feasible solution to alleviate the need of a large swarm size or number of iterations. In α-PSO for selecting the best particle in the swarm, satisfaction level is more important than the objective function value. As swarm is generated randomly, the chances for initial swarm to be scattered ($\mu<1$) in terms of satisfaction level are higher. But one of the constraints ($u_1 \geq 2u_2 \geq \cdots \geq nu_n$) in the mathematical model to evaluate efficiency score expressed in equation 1 always follows a trend, and generating the swarm which follows this trend can increase the chances of producing a swarm with a higher value of satisfaction level. This consideration was adapted in evaluating the efficiency score. The following Figure I.6 exhibits how the swarm travelled to attain the best

position for calculation efficiency score as defined in Equation 9. A swarm size of 25 and 1,000 iterations were used in this analysis.

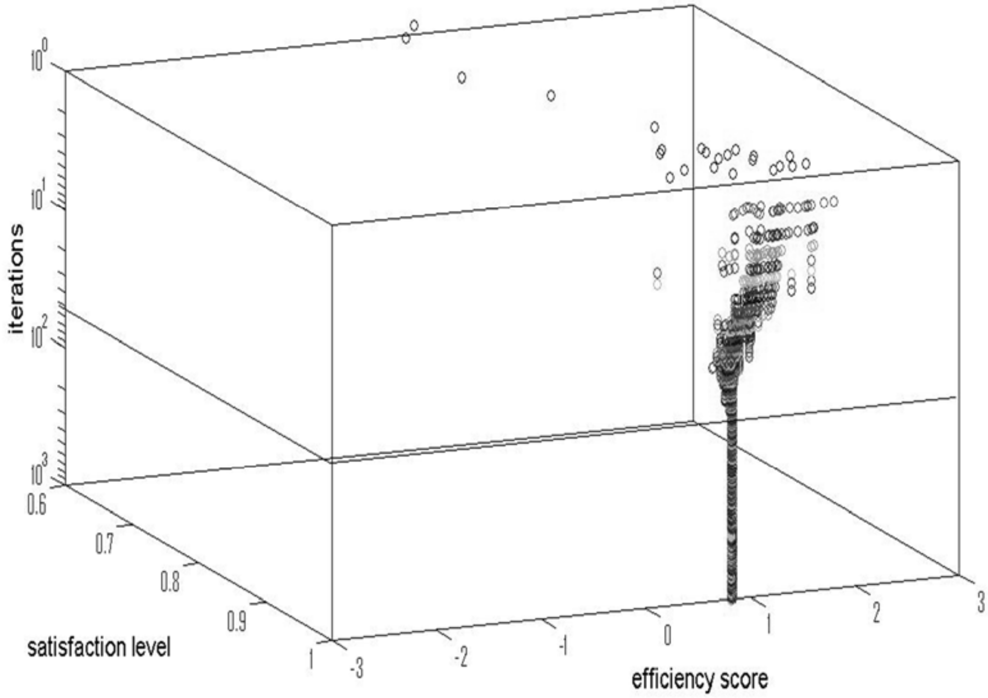
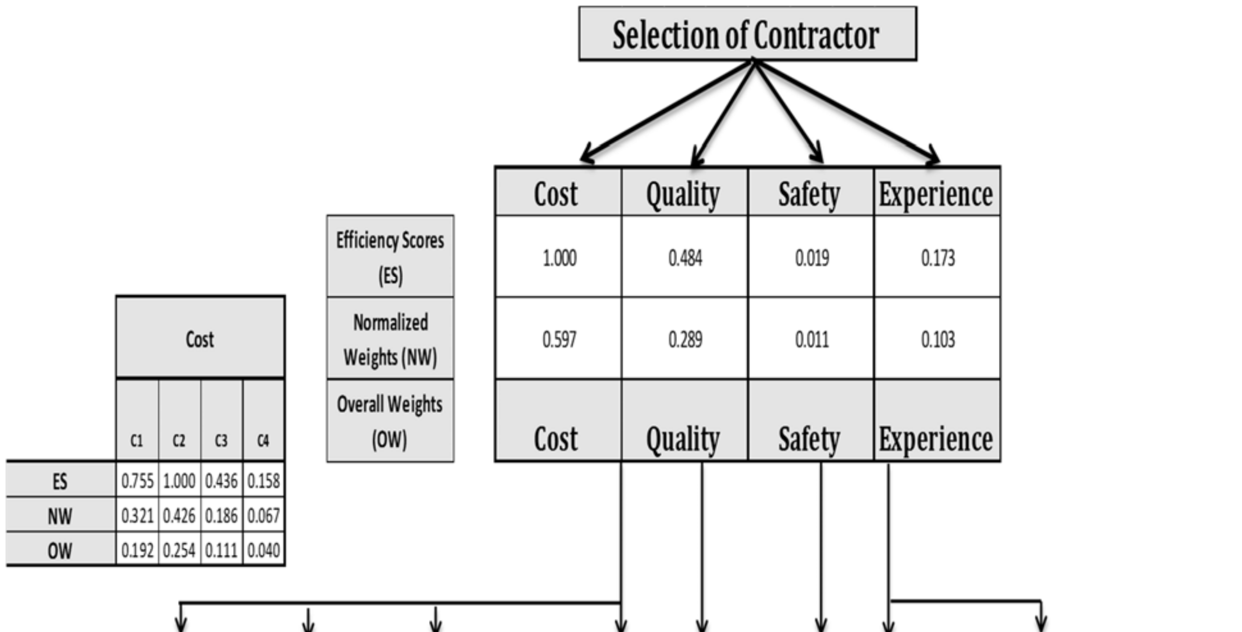



**Figure I.6 Efficiency Score for Contractor 1 Pertaining to Tender Price using Partial Feasible Solution and α-PSO**

All of the particles in the swarm attained the same best position within 50 iterations. On the other hand, it took around 400 iterations for α-PSO. It is apparent from Figure I.5. and Figure I.6. that a partial feasible solution with α-PSO has a better chance of optimizing the solution in fewer iterations. In addition to the above trial, other experiments were done with varying sizes of swarm and the proposed hybrid method was capable of producing the desired results with lower sizes of swarm. The same procedure was applied for aggregating weightages at all levels as stated in Figure I.3.

Both methods (proposed hybrid PSO and α-PSO) were compared for calculation of efficiency scores as shown in Figure I.7. It was observed that the proposed hybrid method out-performed the α-PSO in most of the cases and in few cases α-PSO generated best solution in lower

iterations. As swarm is generated randomly in α-PSO, in some cases the randomly generated swarm was close to the final solution which resulted in lower iterations. The final weightages of each alternative (contractor) were calculated by synthesizing the weightages evaluated for alternatives at various levels. Figure I.7 displays the efficiency scores at each level of hierarchy, the associated weightages, and the final weightages of contractors.




| | Cost | Quality | Safety | Experience |
|---|---|---|---|---|
| Efficiency Scores (ES) | 1.000 | 0.484 | 0.019 | 0.173 |
| Normalized Weights (NW) | 0.597 | 0.289 | 0.011 | 0.103 |
| Overall Weights (OW) | Cost | Quality | Safety | Experience |

| Cost | C1 | C2 | C3 | C4 |
|---|---|---|---|---|
| ES | 0.755 | 1.000 | 0.436 | 0.158 |
| NW | 0.321 | 0.426 | 0.186 | 0.067 |
| OW | 0.192 | 0.254 | 0.111 | 0.040 |

| | Tender Price | | | Financial References | | | Financial Stability | | | Insurance, Repairs and Warranties costs | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ES | NW | OW | ES | NW | OW | ES | NW | OW | ES | NW | OW |
| Contractor 1 | 0.85 | 0.36 | 0.07 | 0.12 | 0.08 | 0.02 | 0.86 | 0.39 | 0.04 | 1.00 | 0.65 | 0.03 |
| Contractor 2 | 0.07 | 0.03 | 0.01 | 1.00 | 0.69 | 0.18 | 0.20 | 0.09 | 0.01 | 0.34 | 0.22 | 0.01 |
| Contractor 3 | 0.02 | 0.01 | 0.00 | 0.05 | 0.03 | 0.01 | 0.06 | 0.03 | 0.00 | 0.08 | 0.05 | 0.00 |
| Contractor 4 | 0.34 | 0.14 | 0.03 | 0.22 | 0.16 | 0.04 | 1.00 | 0.45 | 0.05 | 0.06 | 0.04 | 0.00 |
| Contractor 5 | 1.00 | 0.43 | 0.08 | 0.02 | 0.02 | 0.00 | 0.06 | 0.03 | 0.00 | 0.03 | 0.02 | 0.00 |
| Contractor 6 | 0.06 | 0.03 | 0.01 | 0.03 | 0.02 | 0.01 | 0.02 | 0.01 | 0.00 | 0.02 | 0.01 | 0.00 |
| | | | 0.192 | | | 0.254 | | | 0.111 | | | 0.040 |

| | Quality | | | Safety | | | Reputation | | | Scale of projects completed | | | Final Weightages |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ES | NW | OW | ES | NW | OW | ES | NW | OW | ES | NW | OW | |
| Contractor 1 | 0.76 | 0.26 | 0.07 | 0.89 | 0.40 | 0.00 | 0.19 | 0.11 | 0.01 | 0.19 | 0.11 | 0.01 | **0.250** |
| Contractor 2 | 0.68 | 0.23 | 0.07 | 1.00 | 0.45 | 0.01 | 0.18 | 0.10 | 0.01 | 0.19 | 0.11 | 0.01 | **0.283** |
| Contractor 3 | 0.04 | 0.01 | 0.00 | 0.15 | 0.07 | 0.00 | 1.00 | 0.56 | 0.03 | 1.00 | 0.56 | 0.03 | **0.079** |
| Contractor 4 | 1.00 | 0.34 | 0.10 | 0.03 | 0.01 | 0.00 | 0.14 | 0.08 | 0.00 | 0.08 | 0.05 | 0.00 | **0.224** |
| Contractor 5 | 0.06 | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | **0.097** |
| Contractor 6 | 0.38 | 0.13 | 0.04 | 0.13 | 0.06 | 0.00 | 0.25 | 0.14 | 0.01 | 0.32 | 0.18 | 0.01 | **0.067** |
| | | | 0.289 | | | 0.011 | | | 0.052 | | | 0.052 | 1.000 |

**Figure I.7 Aggregation of Individual Decisions into Group Decision**

The Table I.8 shows the final group weightages for each contractors based on AIP as well as proposed approach (DEA based preference aggregation method combined with α PSO

optimization). Group decision using the AIP method yields Contractor One in the 1st position with a weightage of 0.24. Contractor Two is in the 2nd position with a weightage of 0.23. The difference between the first two ranked contractors is barely 0.01, or 1% which may not satisfy individuals in the group. The proposed approach identified Contractor Two as a first choice and Contractor One as a second choice with a weightage of 0.28 and 0.25, respectively. Although the results from two approaches identify different contractors, the proposed approach is more desirable because difference between weightages of contractors is slightly higher (0.03 versus 0.01). In the fourth column of Table I.8, the results of aggregation and assigned weightage are shown (when a commercially available optimization software TORA is used). The proposed approach and TORA optimization yielded similar results indicating that proposed approach can be used in selection of alternatives. Since proposed approach can be programed and integrated with any Civil Infrastructure GDM, it is a desirable approach. Aggregating the individual decisions with the DEA-based preference aggregation method combined with α-PSO Optimization yielded a clear winner: Contractor Two.

**Table I.8 Aggregation of Individual Decision into Group Decision**

| Contractors | Aggregation of Individual Decisions | | |
|---|---|---|---|
| | Aggregation of Individual Priorities (Arithmetic Mean) | DEA Based Preference Aggregation Method Combined With α-PSO Optimization | DEA Based Preference Aggregation Method Optimized using TORA Software |
| No. 1 | 0.24 | 0.25 | 0.25 |
| No. 2 | 0.23 | 0.28 | 0.28 |
| No. 3 | 0.12 | 0.08 | 0.08 |
| No. 4 | 0.20 | 0.22 | 0.22 |
| No. 5 | 0.10 | 0.10 | 0.10 |
| No. 6 | 0.12 | 0.07 | 0.07 |

### I.6. Conclusions

In this study, weightages were clustered based on rankings and weightages associated with ranks which were then integrated into a DEA model and optimized. The proposed optimized model

for this study is a hybrid constrained PSO. For handling constraints, a combination of partial feasible solutions was combined with the α constrained method. The final weightages calculated using the proposed optimized model were compared with weightages optimized with TORA software. The results indicated that the weightages calculated per the proposed method and those calculated using TORA software are similar.

### I.7. Limitations

This study assumed that all decision makers have equal importance in decision-making. Factors like the experience of decision makers, confidence of decision maker judgments were not considered. Further study is required to include these factors into decision-making.

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# Vita

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