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A Decision-making Tool for Incorporating Cradle-to-Gate Sustainability Measures into Pavement Design

by

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16. Abstract

The objective of this study was to conceive and develop a decision-making tool for evaluating the sustainability of pavement designs and products, based on a cradle-to-gate analysis (where gate is defined as the gate of the construction job site). This tool is based on Environmental Product Declarations (EPD) in order to enhance the reliability and consistency of the analysis. It was developed such that it can be integrated with state-of-the-art pavement design methods such as Pavement ME as well as the AASHTO 93 pavement design method. The developed tool compares the sustainability of different pavement alternatives by computing the environmental and economic performances, thus combining both to assess the overall performance. As a result, the overall performance in turn presents the most cost-effective and environmentally preferable alternative, thus harmonizing engineering performance with environmental and economic performances. The developed decision-making tool evaluates sustainability, based upon analyses derived from EPD, transportation, and economic data, whereby the first two analyses measure the environmental performance, and the third analysis measures the economic performance. The EPD analysis covers the environmental impacts associated with raw materials extraction, transportation, and manufacturing of pavement mixes. The transportation analysis quantifies the impact due to the principal and back haul of pavement mixes from the plant location to the job site, while the economic analysis measures the economic value of an alternative. The developed methodology, which was integrated in a windows-based decision-making software, can assist both designers and decision makers to evaluate and select the most sustainable pavement design/materials as one that meets and balances the criteria necessary for engineering, economic, and environmental performances. The software presents a simple and effective tool, which may be downloaded by designers via the internet, and may be executed in a local computer.

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ABSTRACT

For many years, economic criteria were the dominant factors for the evaluation and comparison of pavement alternatives. However, the growing concerns of major environmental impacts associated with the construction and maintenance of highway systems has increased the interests in sustainability. In the near future, decision makers will need to focus on the incorporation of efficacy in measures to design and construct sustainable pavements. Life-Cycle Assessment (LCA) has presented the most promising tool to measure the cradle-to-grave environmental impacts of a pavement alternative. Yet, the time-consuming nature of LCA, in tandem with limited data, tends to limit the use of LCA in pavement applications. Furthermore, inconsistent assumptions and rules among stakeholders in conducting LCA makes comparisons of pavement alternatives unreliable. Since the application of LCA in pavement applications proves to be challenging, a more efficient tool is needed in the assessment of sustainability. Environment Product Declaration (EPD), a cradle-to-gate sustainability measurement tool, provides accurate and consistent data, thereby addressing the limitations of LCA.

This study developed and integrated a cradle-to-gate (where gate is defined as the gate of the construction job site) framework in a state-of-the-art sustainability measurement tool, framed to select the most sustainable pavement by optimizing a pavement design/mix. The developed tool compares the sustainability of different pavement designs/materials by computing the environmental and economic performances, thus combining both to assess the overall performance. As a result, the overall performance in turn presents the most cost-effective and environmentally preferable alternative, thus harmonizing engineering performance with environmental and economic performances. The developed decision-making tool evaluates sustainability, based upon analyses derived from EPD, transportation, and economic data, whereby the first two analyses measure the environmental performance, and the third analysis measures the economic performance. The EPD analysis covers the environmental impacts associated with raw materials extraction, transportation, and manufacturing of pavement mixes. The transportation analysis quantifies the impact due to the principal and back haul of pavement mixes from the plant location to the job site, while the economic analysis measures the economic value of an alternative.

The developed methodology, which was integrated in a windows-based decision-making software, can assist both designers and decision makers to evaluate and select the most sustainable pavement alternatives as one that meets and balances the criteria necessary for engineering, economic, and environmental performances. The software presents a simple and

effective tool, which may be downloaded by designers via the internet, and may be executed in a local computer.

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Finally, Louisiana concrete companies are acknowledged for their participation in the survey and for providing the inventory data to develop an industry-wide average EPD. We are thankful to them for providing the material costs as well. The research team also appreciate those companies not located in Louisiana but who provided individual EPD, mix design, and material costs.

IMPLEMENTATION STATEMENT

Current pavement design methods in Louisiana are based solely upon engineering performance, rather than the sustainability of a pavement alternative. This study developed a decision-making tool that identifies the most sustainable pavement alternative by balancing engineering performance against environmental and economic performances. The developed decision-making tool is based upon the cradle-to-gate (where gate is defined as the gate of the construction job site) framework and can be integrated into the Louisiana pavement design. The database used in the developed tool is editable and expandable and therefore allows the user to modify the EPD products and cost database as per their regional values, thereby increasing the accuracy of the developed tool.

As the outcome of this study, the developed decision-making tool should be utilized by pavement designers and decision makers in selecting a pavement alternative, which has the least effect on environment and economic components; thereby, reducing the environmental impact associated with pavement construction and operations. It also provides a baseline result for pavement design/mix, thus allowing an easy comparison of multiple pavement alternatives.

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INTRODUCTION

The concept of sustainability is not new; it has been incorporated indirectly or informally in the past *[1]*. However, due to increased awareness regarding environmental impacts from the production, use, and end of product, sustainability has gained popularity. With the increased concern on the environmental impacts, many sectors have adopted different sustainability assessment methods. Because the transportation sector alone contributes to 27% of total greenhouse gas emissions, integration of sustainability assessment methods carries a paramount importance *[2]*. Further, with the increasing demand on the national transportation sector, it becomes imperative that sustainable technologies be introduced that tend to reduce impacts on the environment and social life, while minimizing the cost of maintaining the transportation network *[3]*. Highway systems are an integral part of the national transportation network, which requires a large input of energy, resources, and investment, and has a high influence on the society, due to its widespread use *[4]*. Pavement system presents a high impact to the economic, social, and environmental components. Hence, there is need to design and construct a pavement that would reduce negative impacts on the social, economic and environmental components. A pavement that achieves the aforementioned goals is commonly referred as a sustainable pavement.

Different sustainability measurement tools were developed to indicate and quantify pavement sustainability. Life-Cycle Assessment (LCA), a sustainability measurement tool, was applied to pavement systems dating as far back as the early 1990s *[1]*. Since then, many changes and standard practices have been integrated into pavement LCA. Even though LCA is still evolving, it represents a widely used technique to quantify the environmental impacts of pavement systems *[3]*. However, the application of LCA to pavement is challenging because it requires a wide range of resources in order to compile the data for analysis. Further, its time-consuming nature, coupled with the availability of data, tends to impact results accuracy *[5]*. Since LCA is still evolving, a variation of assumptions, methodologies, and interpretation exist among stakeholders. This variation may result in different impact values for the same pavement product *[6]*. Due to these reasons, the comparison of pavement alternatives using LCA is a challenging task.

Environment Product Declaration (EPD), an emerging sustainable measurement tool, addresses the limitations of LCA. EPD applies consistent industry standard rules to define the environmental impacts due to the raw materials acquisition and production, transportation from extraction site to plant location, and manufacturing *[7]*. EPD provides meaningful metrics that can be used for the comparison of products at both local and state levels. The inventory database provided in EPDs alleviates the data-collection burdens *[1]*. An EPD, obtained from life-cycle assessment in accordance with the international standard ISO 14025 (Type III Environmental Declaration), presents a standardized, third party, and verified document that reports the product environmental impacts. Product Category Rules (PCR) define the EPD rules, which in turn are developed by the program operators as per ISO 14025 specifications , thus considering the cradle-to-gate cycle of a product *[7]*.

One drawback of EPD is that as a tool, no consideration exists for the economic aspects of the pavement product/design. Combining EPD with economic criteria would provide an effective approach in the selection of a pavement design/product alternative.

Literature Review

Pavement Sustainability

Pavement systems significantly alter the environment, economic, and social components *[4]*. These three components are collectively termed as "triple-bottom line." Of all these components, the economic component presents the main leading factor for the decision-making process *[1]*. With an increase in awareness regarding the effect of pavement systems on the environmental and social components, many decision-makers attempted to account for these components as well *[4]*. Hence, a pavement system, which considers all triple-bottom line components as important, is deemed a sustainable pavement. In other words, pavement sustainability is defined as a system characteristic that not only achieves its intended engineering goals, but also meets basic human needs, i.e., health, safety, equity, employment, comfort, and happiness by optimizing human, financial, and environmental resources and preserving the surrounding ecosystems *[4]*.

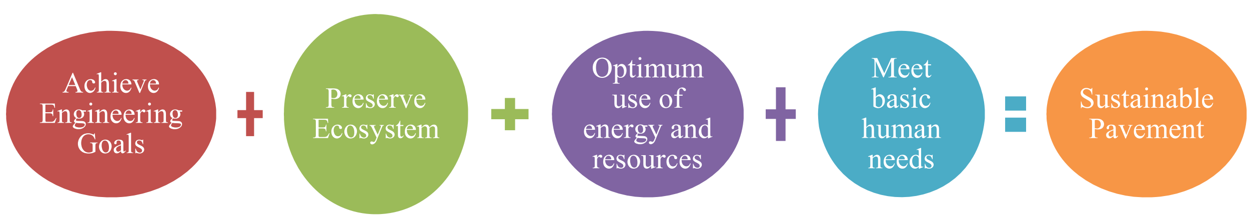


Figure 1
Characteristics of a sustainable pavement

Pavement Life Cycle

Each stage of a pavement life cycle has a significant impact on the environment. Before discussing the different sustainability measurement tools, it is important to describe the phases that a pavement experiences from the initial design stage to the end of service life. Each sustainability assessment tool considers different phases of a pavement life cycle as shown in Figure 2. Different assessment approaches, as detailed in Appendix A, have been integrated into the different phases of a pavement life cycle.

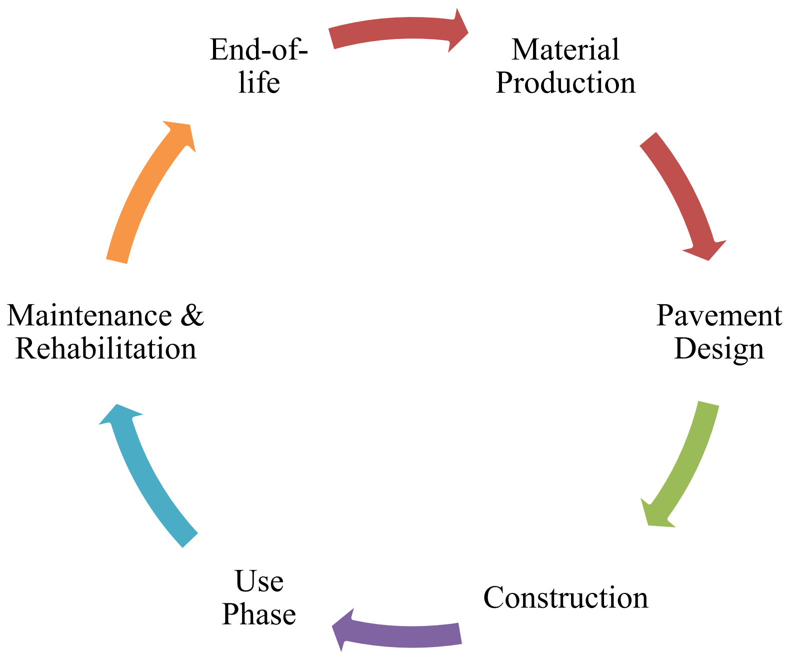


Figure 2
Pavement life cycle stages

Material Production. Material production includes all processes associated with raw materials acquisition, transportation, and material production (manufacturing of the finished product from the raw materials), mixing process (e.g., production of concrete and asphalt concrete mixes) and transportation of mixes to the job site *[8]*. This is commonly referred as a cradle-to-gate framework.

Pavement Design. This stage determines the functional and structural demands of a proposed pavement system and results in a pavement, which meets the targeted goals by considering environmental and traffic conditions. The stage also governs the pavement structural compositions, i.e., the number of pavement layers, materials, and the corresponding thicknesses *[4]*. Apart from engineering performance criteria, many state agencies now incorporate different sustainability measures in this stage to account for the environmental, economic, and social performances. A summary of the practices adopted by Departments of Transportation (DOTs) is illustrated in Figure 3. Details of sustainability measures and innovative analysis tools are discussed in Appendix A.

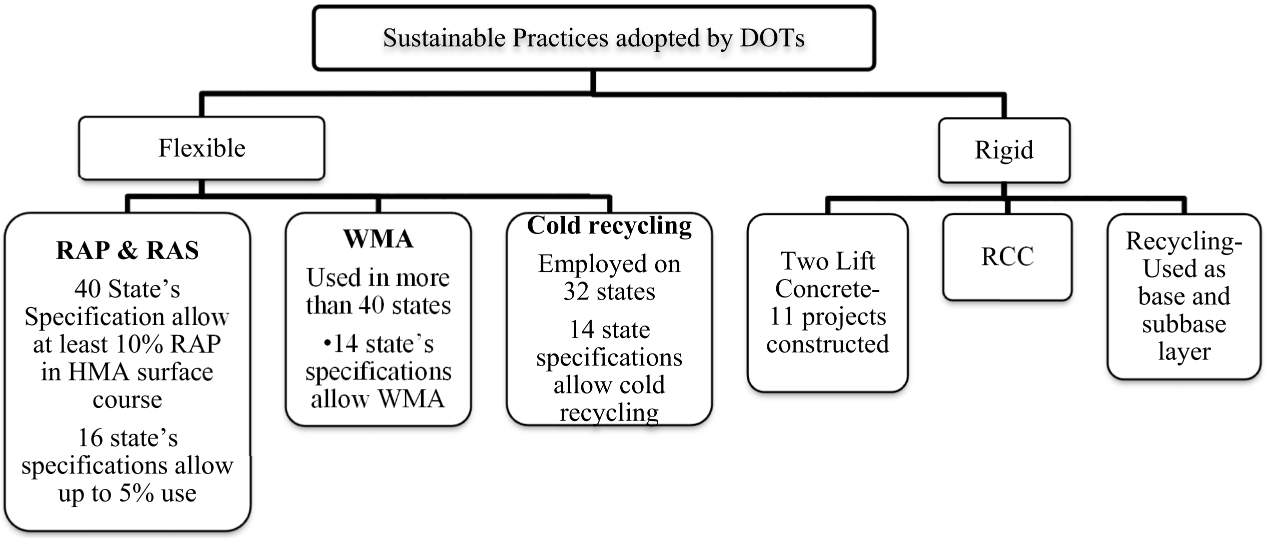


Figure 3
Construction practices adopted by different DOTs

Construction. This stage considers all the activities and impacts associated with the equipment transport from and to the site, laying, and compaction of the pavement mixes by different equipment, disposal of any waste, and the energy used for night construction *[8]*. This stage should also account for the impacts due to traffic delay during construction *[1]*. Different efforts for integrating sustainability in the construction phase of pavement are explained in Appendix A.

Use Phase. The use phase of a pavement is the life after construction until the end of its life. In other words, it is the phase where the pavement is in service, interacting with the environment and traffic. A correlation exists between pavement characteristics and impacts during the use phase. Pavement characteristics include structural responsiveness, macrotexture, roughness, permeability, albedo, heat capacity, and conduction *[1]*. Many studies have excluded this phase from the system boundaries due to the unavailability of data.

Maintenance and Rehabilitation. Pavement structural and functional capacity decrease with time. These characteristics result in different distresses, which may be unsafe and uncomfortable to the users. Hence, in a timely manner, different activities are conducted to maintain the overall serviceability of the road. These activities are referred to as maintenance and rehabilitation (M&R). The frequency and the type of the M&R work are dependent upon the pavement type, design, traffic, and environment conditions. For an accurate sustainability measure, it is essential to quantify the appropriate frequency and type of M&R activities. This phase presents a significant contribution to the overall environmental impacts.

End-of-Life. When pavement reaches its end of life, some materials are available for reuse, recycle, or disposal *[1]*. This phase includes all the processes associated with the production of recycled materials such as Reclaimed Asphalt Pavement (RAP) and Recycled Concrete Aggregate (RCA) *[8]*. If recycled materials are used in a new pavement, a proper allocation method for allocating of impacts and benefits is necessary. If not recycled, this phase accounts for impacts, which are related to transportation to a landfill or disposal site.

Measurement of Pavement Sustainability

The measurement of pavement sustainability is needed in order to benchmark or to compare pavement design alternatives. There are different approaches to measure pavement sustainability, but there is no standard practice for the quantification of pavement sustainability. Each sustainability measurement tool has its own strengths and weaknesses. Depending upon the approach, a sustainability measurement tool can be categorized as quantitative and qualitative. The quantitative method adopts models and empirical formula to obtain a value, which in turn quantifies the sustainability of a pavement. Whereas a qualitative approach is based on methodological and conceptual approaches to collect and gather information on economic, social, and environmental performances of a pavement system in order to provide a rating or score to the considered pavement alternatives. The rating or score reflects the sustainability of a corresponding pavement alternative.

Qualitative Approach (Sustainability Rating System). The qualitative approach is a collection of practices or features that alter the environment, economy, or social values, coupled with a uniform method of measurement score, normally a point *[1]*. There are different sustainability rating methods. The selection of the most reliable sustainability tool is dependent upon the nature of the rating system and per the goal of the project. For a sustainability measurement, information data on the type, range, and impacts, which are due to the pavement system, are collected. The collected information, together with a collective list of sustainability measures of a rating system is then used to obtain the total sustainable rating or score of a design alternative, which in turn represents the relative impacts. Green roads, ENVISION, Infrastructure Voluntary Evaluation Sustainability Tool (INVEST), The Sustainability Tracking, Assessment & Rating System (STARS), Green Highway Partnership (GHP), GreenLITES, I-LAST, and BE2ST-in-highways, Sustainable Transportation Environmental Engineering and Design (STEED), and the Sustainable Infrastructure Project Rating System (SIPRS), are examples of national and international rating systems that have been developed. A detailed description of the different sustainability rating systems is provided in Appendix B, and a summary of commonly used sustainability rating systems is presented in Table 1.

Table 1
Sustainability rating system

Tool Name	Developed by	Launch date	Type of rating
INVEST	FHWA's Sustainable Highways	October 2010	Self-Evaluation
STARS	Public-private team from Oregon and Washington	Mid-2012	Third-party certification
Greenroads	University of Wisconsin, CH2M Hill, and Washington State Department of Transportation	January 2010	Third-party certification
GreenLITES	New York State Department of Transportation	2008	State DOT administered Self - evaluation
I-LAST	IDOT	2010	Self-Evaluation
BE^{2}ST-in-highways	University of Wisconsin	2010	Self-Evaluation
GHP	Public-private initiative with support from EPA, FHWA, and MDSHA	2010	Self-Evaluation

The strength of this approach is in the coverage of a wide range of aspects and practices such as disruption to neighboring land due to construction, wastes from pavement construction, recycled materials used in pavement system, ecosystem connectivity, and the like. This method allows for alternative comparison and decision making, measuring the sustainability measure either by accounting for all best practices with an equal point value or by weighing only the best practices. The latter one is more useful in case of a limited budget or scope, as it assists in selecting the most impactful practices *[1]*. Since this method assigns common metrics to a wide range of sustainable practices, it sometimes generates consensus on which item to include or exclude. The weakness of this approach is that the method does not quantify the total environmental impacts as in LCA. With the change in the criteria adopted by the Leadership in Energy and Environmental Design (LEED) system, which now requires a quantitative measure of the environmental impacts, agencies and organizations are gradually moving from qualitative measures to more quantitative measures.

Quantitative Approach. A quantitative measurement tool is a rational method, which is either based on empirical formula or developed by building a model to quantify the performances of each triple bottom line component. The resulting impact value is associated with the different phases of a pavement life cycle. Not all quantitative methods quantify the impacts associated with the entire pavement life cycle. Some methods consider a cradle-to-gate framework, while others consider a cradle-to-grave framework. The inclusion and exclusion of pavement life cycle stages are dependent upon the characteristics, constraints, goals, and demands of the respective project. Out of many approaches, the three relevant tools for quantifying the sustainability of a pavement system are discussed in this section.

Performance Assessment. Performance assessment evaluates pavement performance by comparing it to the intended function. Since this method compares pavement alternatives to existing performance standards, this method does not need differing standards to incorporate pavement sustainability. The main criterion for the comparison is that the proposed pavement alternative should at least perform equal to or more than the current standard practice. Pavement performances are generally addressed in terms of specific physical attributes and behavior mechanisms. Some of the parameters for measuring pavement performance include performance condition ratings, pavement structural capacity, pavement ride quality, and frictional characteristics. This method is easily implementable and requires no expert for an assessment; yet, the method accounts for no other benefits of the considered pavement alternative. A list of the states that use performance assessments in different phases of pavement life cycle is presented in Table 2.

Table 2
Rating systems applied by different states *[9]*

Pavement life-cycle phase	Adopted by
Planning and programming	Maryland, New Jersey, Minnesota, Wisconsin, California Department of Transportation (Caltrans), Washington, Oregon, Florida, Metropolitan Transportation Commission (MTC), Denver Regional Council of Governments (DRCOG), North Jersey Transportation Planning Authority(NJTPA), Ohio, Chicago
Project development	Caltrans and NJPTA
Construction	Wisconsin, Washington, New York State Department of Transportation (NYSDOT), Los Angeles
Maintenance and system operations.	Washington, Oregon, Colorado, New York Metropolitan Transportation Authority (NYMTA), Los Angeles

Life-Cycle Cost Analysis (LCCA). With the increase in cost related to highway maintenance and rehabilitation in tandem with the limited amount of funds, highway decision makers have incorporated cost analysis tools to determine the most long-term and cost-effective pavement alternative *[10]*. Life-cycle cost analysis, which is based on a cradle-to-grave framework, determines the total cost of pavement including initial costs, maintenance and rehabilitation, and end-of-life as well; see Figure 4. ISO 15686-5 defines LCCA as a technique for estimating and assessing economic performance by considering all the relevant economic factors (both initial and future costs) of different assets that meet the functional, operational, and other requirements. The inclusion of all or a partial pavement phase is dependent upon the goals and characteristics of a project.

The Federal Highway Administration (FHWA) encourages implementation of LCCA in all major investments, which have a high influence on a wide range of sectors. LCCA's involvement in pavement design started with ISETA in 1991, which required the consideration of life cycle costing in the design and engineering of pavements *[11]*. Further, Executive Order No. 12893, "Principles for Federal Infrastructure Investment" in January 1994 made it mandatory to analyze benefits and costs when making infrastructure investment decisions considering the full life cycle of each project *[12]*. The National Highway System (NHS) Designation Act of 1995 requires that states implement LCCA on NHS projects. The program is required when the cost of a usable project segment either equals or exceeds $25 million. LCCA may be used in other areas of pavements, such as prioritization and allocation of resources, as well as a funding selection level *[13]*. Furthermore, the 1995 NHS Designation Act recommended that the level of details in LCCA should be consistent with the level of investment, i.e., major to minor to insignificant by an inclusion of all the factors, as well as an explanation of the rationale for eliminating factors *[13]*.

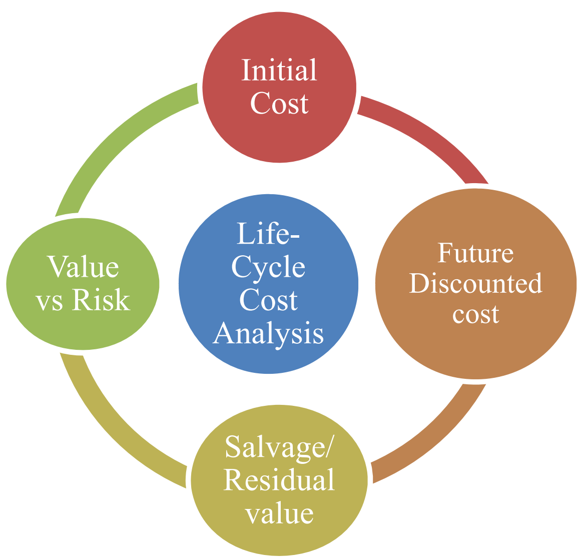


Figure 4
LCCA analysis framework

LCCA is divided into three distinct categories − conventional, environmental, and societal *[14]*. The conventional LCCA considers the monetary values, which are directly covered by the producer or user in the life cycle of a product. The environmental LCCA is one where environmental damage that is due to the product life cycle is estimated and monetized. It is necessary that environmental LCCA be carried out in conjunction with life-cycle assessment. Finally, LCCA can include the costs for the society by extending the analysis to the macro-economic system level; in this case, the LCCA is deemed a societal LCCA *[14]*.

The life-cycle cost of a product can be estimated by two different approaches, deterministic and probabilistic. The deterministic approach utilizes distinct values and therefore does not account for uncertainties. This approach does not account for uncertainties and as a result, lacks statistical values for the output. This method may estimate an inaccurate value and thus misinterpret the results in the decision-making process. Therefore, a sensitivity analysis is usually conducted to specify whether the variable input might influence the estimations. This process may lead to a higher accuracy and confidence in decision-making *[4]*.

On the other hand, the probabilistic approach accounts for uncertainties (applies a statistical analysis to account for the input variation) and provides a value in a certain range. Since this approach addresses the weakness of the deterministic method, it gives more reliable and accurate results. Rather than a single output, this method provides a range of values. The user can then distinguish the differences and confidence levels to be placed in the analysis *[4]*. The life-cycle cost of the product can be determined by Net Present Value (NPV), Equivalent Uniform Annual Cost (EUAC), benefit-cost analysis, and Incremental Benefit-Cost (IBC) analysis.

In the context of pavement, different studies were conducted to apply LCCA in pavement projects. Santos et al. (2015) conducted a comprehensive pavement LCCA to determine the most cost-effective M&R strategies by considering the entire six phases of the pavement life cycle *[15]*. Similarly, FHWA developed a framework to determine the cost-effectiveness of pavement rehabilitation strategies. The framework was inclusive of four steps: (1) pavement conditions and analysis module, (2) selection of appropriate maintenance and rehabilitation strategies, (3) determination and ranking based on the cost and benefits of each strategy, and (4) selection of the most cost-effective strategy. These studies considered only the economic aspect of the proposed strategy while they did not account for non-economic factors in the analysis *[16]*.

The main limitation of LCCA is that it does not account for the level of performance. Comparison of the two alternatives showing different levels of performance using LCCA does not provide reliable results. Furthermore, the lowest life cycle cost does not represent the most sustainable product, since it solely considers the economic aspects of the design. Furthermore, the lowest life cycle cost does not account for the monetary values of social benefits or the environmental impacts. In this regard, LCCA provides balanced results when integrated with LCA. With a developing progress in monetization of environmental impacts, LCCA can provide results that are more balanced.

Regarding user costs, however, there is a conflicting viewpoint, so that LCCA differs from one study to another for similar pavements. The deviation in the life-cycle cost of similar pavements in different studies is also due to challenges faced in the selection of a discount rate, user costs, and an end-of-life value. The desired discount rate in pavement projects should be determined based on historical tendencies over extended periods of time and near-term projections. According to FHWA, federal agencies usually use the guidance prepared by the U.S. Office of Management and Budget (OMB)-Appendix C in order to select an appropriate discount rate. The effect of a discount rate on LCCA is most critical. Therefore, it is important to choose the correct discount rate *[4]*. User costs may not be included in the cost analysis, if the focus is on agency expenses. According to FHWA, several reasons exist to justify this action. First, there are many conflicting points of view toward user costs, which make it difficult to reach a consensus on a standard procedure to estimate user costs accurately. Furthermore, previous experiences indicated that user costs could be too high for the agencies to account for these costs *[4]*. Hence, user costs should be considered in a separate analysis, rather than combining them with agency costs. RealCost LCCA program, a free software provided by FHWA, and CA4PRS developed by Caltrans are the most popular tools, which can be used to compute user delay costs *[4]*.

The proper allocation of benefits due to the residual value, either as salvage value or as a remaining service life value, should also be considered in LCCA. This alters the benefits to the agency regarding residual value and thereby affects the overall results of LCCA. Due to the limitations of LCCA, it should be used as a support tool, rather than a decision-making tool.

Best Economic Practices Adopted by State DOTs. Economic factors play an important role in pavement projects. Due to budget limitations, it is imperative that different cost analysis methodologies be incorporated into the selection of pavement alternatives. Hence, different types of cost analysis tools have been developed to identify the most cost-effective pavements. Table 3 presents the different economic practices adopted by state DOTs; economic practices in different states are detailed in Appendix C.

Table 3
List of economic practices adopted by DOTs *[17]*

State	LCCA Tool	Analysis Period (Years)	Discount Rate (%)	User Costs Included
California	RealCost	20, 35, 55	4	*Yes*
Colorado	RealCost	40	Determined annually	*Yes*
Florida	RealCost	40	3.5	*Optional*
Georgia	Custom spreadsheet	30, 40	3	*Yes*
Illinois	Not specified	45	3	*No*
Indiana	RealCost	At least 50 (for new)	4	*Yes*
Michigan	DARWin and custom software	10 to 20	Determined annually	*Yes*
Minnesota	Custom spreadsheet	35 to 50	Determined annually	*No*
New York	Not specified	Range	4	*No*
Ohio	Not specified	35	Range of 0 to 6	No
Oregon	Real Cost	40 (new) 50 (Interstate)	4	Optional
Pennsylvania	Custom spreadsheet	50	4	Yes
Texas	Custom software	30	Not specified	Yes
Utah	Not specified	25 to 40	4 (recommended)	Yes
Virginia	Not specified	50	4	No
Washington	Real Cost	50	4 (based on OMB)	Yes

Life-Cycle Assessment (LCA). Life-Cycle Assessment (LCA), a cradle-to-grave process, presents a methodological framework to quantify environmental impacts due to a product, system, or process across its entire life cycle *[1]*. As illustrated in Figure 5, LCA requires the input of resources and energy consumption, and provides results in the environmental impacts, which are categorized into different impact categories due to the different phases of pavement life cycle. Even though LCA was first applied to pavements in the early 1990s, LCA is still considered in the research phase. The appropriate method for selecting a sustainable pavement design is by predicting where the significant amount of impacts will be produced in the pavement life cycle. LCA not only quantifies the total environmental burdens related to the product's life cycle, but it also identifies where the significant impacts will be produced and thereby predicts any potential, unintended consequences by accounting for all inputs and outputs *[4]*. Further, it provides an opportunity for significant improvements. Due to the benefits of LCA, it represents the most used sustainability quantification tool in pavement applications.

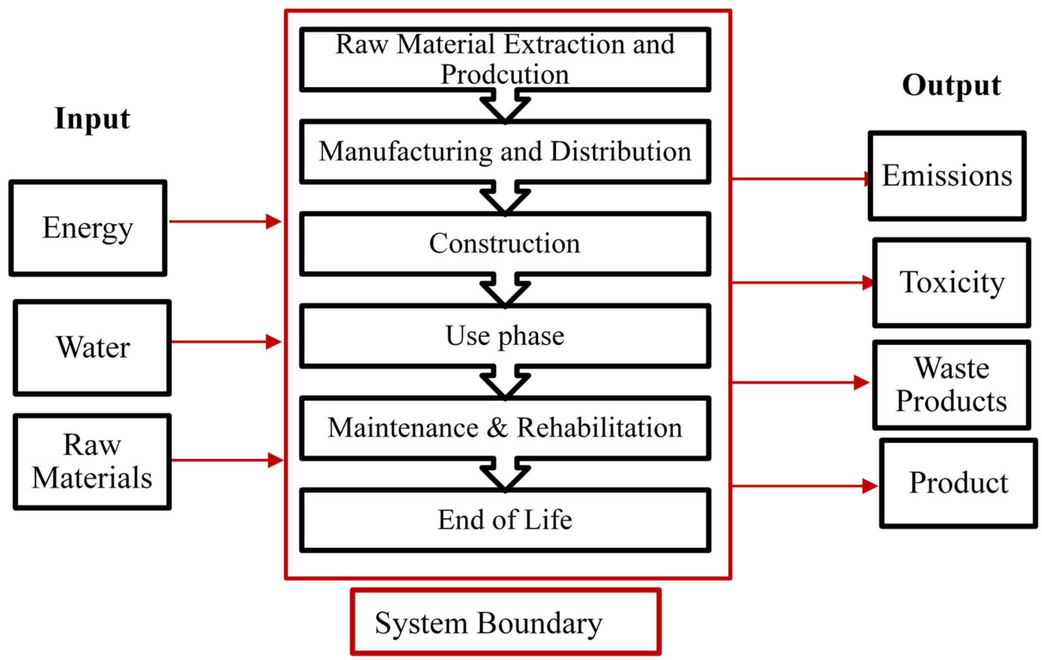


Figure 5
Life-cycle impact assessment framework

The LCA framework consists of four major steps (ISO 2006a): (a) goal and scope definition, (b) life-cycle inventory assessment, (c) life-cycle impact assessment, and (d) interpretation, see Figure 6.

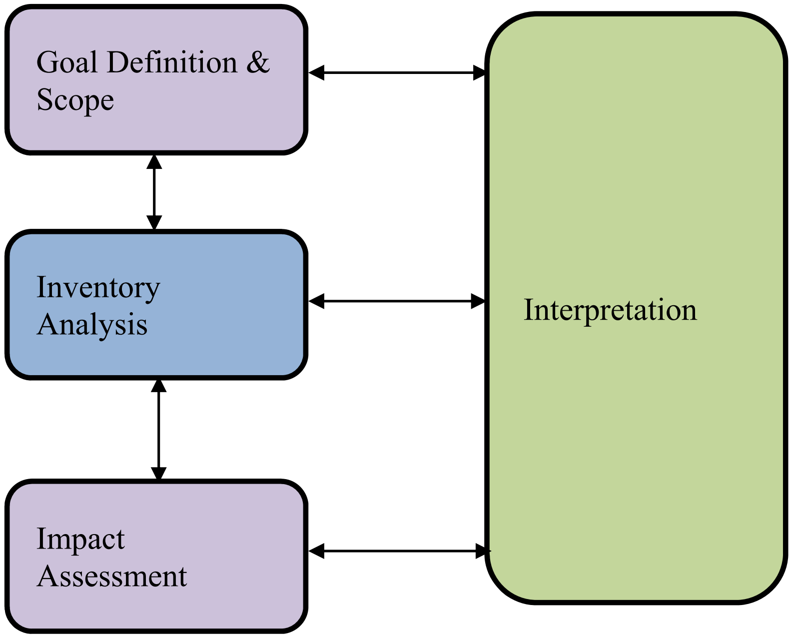


Figure 6
Life-cycle assessment stages *[4]*

Goal and Scope Definition. The first phase of LCA, goal and scope definition, defines the purpose and method of the study. A well-defined goal and scope results in more accurate results by determining the type of information needed, the required accuracy of data, system boundaries, and functional units. The main step involved in goal and scope is defining the objective of the study, functional unit, and system boundaries. The objectives of pavement LCA can be benchmarking, comparison of rigid and flexible pavements, comparison of pavement rehabilitation strategies, or hotspot analysis. A literature review of past studies showed that among 32 pavement LCAs, 21 studies were conducted for comparisons between pavement types; the remaining were conducted for strategies comparison for the same pavement type.

This phase should also identify the type of information required by defining the type of pavement LCA, either an attributional or a consequential LCA. An attributional LCA uses values from averaged data based on normal business practices. Attributional LCA reduces consequences, and as a result, requires marginal data. Although attributional LCA incorporates a fixed system boundary, the consequential LCA system boundary may be expanded, depending upon the overall goal of the LCA. Therefore, it is important to define the type of LCA.

Together with defining the type of LCA, defining the functional unit is equally important in the analysis. The functional unit represents the quantified performance of a product system for use as a reference unit for the LCA study; whereas, the declared unit is used when a precise function of the product/process/service is not stated or known, or when the LCA does not cover a full life cycle, i.e., EPD. A literature review of past studies showed that different studies used various functional and declared units. About 37.5% of studies used lane miles or lane kilometers; whereas, research that studied surface materials used a square meter declared unit. Some studies even used 5 km or 10 km. The variation in a functional unit can result in difference in the results. To reduce the gaps of such a shortfall in future studies, FHWA has provided guidance for the determination of a functional unit. A functional unit should be characterized, based on the location, application, physical boundary definitions and dimensions, performance standard, and analysis period. For pavement, it is important that the functional unit includes physical dimensions, such as length, width, or thickness, and includes indicators of pavement performance and the criteria of performance *[1]*. The consideration of an equivalent functional unit is necessary to guarantee that compared pavements, materials, or projects will provide similar performances.

Another important aspect is to define the system boundary. Defining system boundaries in a wrongful way or omitting processes can lead to a 50% error in the results *[1]*. Past studies in pavement LCA have considered only materials extraction and production; whereas, end-of-life cycle and use phase were excluded. The inclusion of end of life is essential to account for the recycling benefits of old pavement materials. Asphalt materials have a high recycling potential in comparison to concrete pavements; exclusion of this phase alters the output of the results when comparing rigid and flexible pavements. Similarly, the assumption that all pavements cause the same environmental impacts in the use phase is not a valid assumption. A study by Wang et al. (2012) claimed that the impacts of the use phase vary depending on pavement conditions, roughness, and pavement vehicle interaction *[18]*. The sole reason the use phase was not considered in past studies is attributed to limited impact assessment studies performed in the use phase.

Together with the aforementioned objectives, this phase of LCA should define the required level of details by identifying whether the unit processes data (generic/product-specific) or industry average data, are to be used. The challenges of unit process modeling are data unavailability or data, which are not representative for the specific unit process. A combined/aggregated model process would address these limitations but it would not provide flexibility and transparency.

Life-Cycle Inventory (LCI). The second phase of LCA involves the collection of data for all the inventory flows to and from the system *[1]*. The flow diagrams are developed to map the input and output of each unit process. All the intermediate flows (shown in the diagram) and elementary flows (usually not shown in the diagram) should be identified for each unit process within the flow diagrams. One of the significant aspects of LCI is the allocation procedure. ISO 2006b defines allocation as a “partitioning of the input or output flows of a process or a product system between the product system under study and one or more other product systems" *[19]*. ISO standards recommend avoiding allocation procedure, if possible. If not, allocation by mass, volume, or economic value may be used to partition the relation between inputs and outputs of the total product system. *[1]*. Allocation procedure may be selected in such a way that it should represent the most appropriate relationship between different parameters. Use of Supplementary Cementitious Materials (SCM) in cement concrete, production of asphalt in oil refinery, and use of recycling materials, etc., are cases where allocation is recommended *[1]*. Pavement uses a large amount of recycled materials; hence, proper allocation should be accomplished to partition the corresponding environmental benefits to the new pavement and old pavement.

Another main aspect of this phase is that the data collected should meet the level of accuracy, as defined in the overall goal of the study. Depending upon the defined goal and scope, location-specific data should be used. Due to the unavailability of local data, most of the studies in the past have used national average data. For instance, Wang et al. (2012) used a database from California; Cass and Mukherjee (2011) drew data from Michigan, and Weiland (2008) utilized data from Washington State *[18], [20], [21]*. National average databases such as ISO 14040 and the Portland Cement Association (PCA) were also utilized as life-cycle inventories. In addition, some studies used inventory databases available in commercial software *[22], [23], [24]*. Since some emissions are highly influenced by the location, using the national data for such scenario would reduce the accuracy of the results. Hence, users are always encouraged to use local data for LCA analysis, if possible.

Along with data suitability per location, the collected data must be examined against the requirements of the data quality. Data quality can be checked by precision, representation, completeness, consistency, and reproducibility. These choices are commonly referred to as data quality indicators. Mass balance, checking consistency, and checking for outliers complete the tools for data quality indicators.

The data collected in this phase can be acquired either as primary, secondary, or from both sources. Depending upon the sources of data, LCA can be classified as a process-based LCA, Input-Output (I-O) LCA, and Hybrid LCA. A process-based LCA consists of an environmental analysis method that computes the inputs and outputs of every activity considered within the system boundary for a given product or service. Since each environmental emission related to individual processes is quantified, a process-based LCA necessitates that the system boundary be well defined. Since this is the most-detailed approach, LCA encourages use of the process-based data, if possible. This approach is time-consuming; therefore, LCA operators selectively analyze these different processes, which may result in truncation errors *[25], [26]*. On the other hand, Input-Output (I-O LCA) modeling represents a top-down approach that approximates the sector level environmental loads, as well as the resources consumed throughout the upstream supply-chain. I-O LCA generates a certain amount of different goods and services by means of using the available sectorial monetary transaction to describe complex industry interdependencies *[27]*. This approach considers the relationship between different economic sectors to determine how the output of one industry transfers to another industry, where it serves as an input. Even though I-O LCA decreases the burden of data collection and is fast and inexpensive, the uncertainty related to the prices, when combined with the lack of data for use phase and end of life cycle, discourages the use of the I-O LCA model. Further, the data in this method is relatively dated. Thus, assessing rapidly developing sectors and new technologies may introduce errors due to base-year differences between the product system under study and the I-O data. The incompleteness of data in this method reduces the accuracy of the results of the environmental impacts, thereby deviating the compiled results from the actual results *[28]*. The unit process and I-O LCA approach provides a certain level of strength and weakness, to which most LCAs combine both methods, known as Hybrid LCA. The term *hybrid* is usually used for the integration of sector and process-level data. The hybrid approaches are usually classified into three categories: i) tiered hybrid analysis; ii) input-output based hybrid analysis, and iii) integrated hybrid analysis.

Identification of the data types, sources, and required accuracy is followed by a data collection procedure, which involves interaction and contact by means of a wide range of industries and visit to the sites. Data collection can be less time consuming, by use of the commercially available data packages that meet the required level of data quality. Non-site-specific inventory data such as that from US LCI and other organizations can be used. If there is lack in the required level of data, the system boundaries should be changed as per the available data; hence, LCA is known as an iterative process. In the end, every LCI should document all the collected data and the outcome in the form of wastage, materials, and energy consumed. Along with the methodology used and system boundaries analyzed, if any, the assumptions and limitations during the life cycle inventory should be properly documented. The developed LCI requires a third-party review, if the targeted audiences are public.

Life-Cycle Impact Assessment (LCIA). LCIA, the third phase of LCA, converts the LCI into environmental and human impacts using an impact chain, such as a cause and effect chain of environmental flows on humans, the natural environment, or the depletion of the natural environment. LCIA requires selection of a set of impact categories, an impact category indicator, and a characterization model that reflects a comprehensive set of environmental issues related to the considered product. For each selected category, the results of LCI are assigned to the respective categories. A characterization model and factor values account for how much each impact category indicator contributes to the impact categories. The adopted characterization factor is multiplied by the respective emission values from a life-cycle inventory to quantify the overall impact of each category. The EPA establishes three main groups of environmental impacts: 1) human health, 2) ecological health, and 3) resource depletion *[29]*. Based on these groups, the EPA identifies the following life-cycle impact categories: 1) global warming potential, 2) warming potential, 3) acidification, 4) resource depletion, 5) land and water use. Energy consumption, and GHG emissions (specifically, carbon emissions) are typically the main emissions considered in pavement LCA. This is because the impacts of energy and GHG emissions are easily explainable, and therefore cause no over-complexity *[30]*.

There are many ways to calculate and visualize different impact assessments; the midpoint and endpoint method are the most common. The main distinction that exists between these two is that each considers different stages of the cause-effect to analyze the results. The indicators, which are selected before the end of the impact chain, are termed midpoint indicators, whereas the ones that consider the full impact chain (with an effect on environment and health) are called endpoint indicators. Global warming potential, ozone layer depletion, and acidification potential are common mid-point indicators. The same factors are represented as the results of eco-system loss due to sea-level rise, skin cancer due to UVB radiation, and forest tree loss due to acidification, in end-point indicators *[1]*. All the flows and impact categories relevant to the goal of the study should be included. Since the impacts differ from place to place, it is important to identify the geographic scope of the indicators, which can be local (i.e., some air quality measures, particulate from traffic), regional (acidification, eutrophication) and global (global warming, global resource depletion, etc.) The global model generally underestimates the impacts but can have wide application, whereas the regional has better results and precision, yet can have a limited applicability. It is recommended that the impacts be calculated based upon regional rather than international or national values, as many impacts are dependent upon the emission site *[1]*. The widely used impact categories in the US are defined according to the TRACI assessment methodology developed by the EPA.

Together with the impact categories, the LCA should distinguish and report the various energies separately, such as resource use (energy vs. material), resource renewability (renewable vs. non-renewable), and resource origin (nature vs. the economy). It is also necessary to report feedstock energy separately (energy stored within the material), to ensure that the energy stored within the material is not counted twice. Current practice in North America is to separate feedstock energy from the total energy consumption. The method of separation of feedstock energy is relevant in the case of petroleum-based products. In a pavement LCA, the consideration of feedstock energy is relevant to asphalt pavements and the use of oil-based plastics and other materials. Feedstock energy is the main indicator that represents non-renewable energy for asphalt pavements. In LCA analysis, feedstock energy covers use or depletion of non-renewable energy. As mentioned earlier, it is suggested to represent feedstock energy separately. Separation of feedstock energy for binder is suitable from a recycling point of view as well since it avoids any double counting that might occur if it is not reported separately *[1]*.

The LCIA results may be further interpreted by normalization, grouping, and weighting:

- **Normalization:** The computed impacts are in non-commensurate units, i.e., GWP represented in $KgCO_2eq$, acidification in hydrogen ion equivalents, etc. Normalization synthesizes the computed impacts into a common scale depending upon a reference value.

- **Grouping:** It is the process of assigning the impact categories into one or more sets as per the nominal grouping, ranking or sorting. It can be done as per the scale of the impact category or the unit process or as per the LCA phase.

- **Weighting:** Each impact categories are converted based on a set of weights, reflecting the relative importance to the overall environmental performance. It is recommended that both results, prior and after weighting, are available.

One of the limitations inherent in impact assessment is the lack of consideration of the different impact groups, such as resource depletion and human health. Resource depletion and human health result in environmental impact assessment problems. For instance, noise is an important environmental impact, often neglected by pavement LCA studies. By examining past pavement LCA studies, it is noted that only two studies considered noise as an environmental impact *[31], [32]*. Both studies agreed that concrete pavement produced a higher level of noise, compared to Asphalt Concrete (AC) pavement alternatives. However, noise is problematic to quantify, due to the lack of data. Another important observation is that some studies omitted the impact assessment step in LCA, and as a result, did not quantify the environmental impacts.

Interpretation. Interpretation is the last phase of the LCA analysis where all the results (from either LCI or LCIA) are presented in terms of a functional unit, and the major contributions are identified and explained as to where the impacts are most effective. Interpretation methodology should be clearly defined in the goal and scope phase of LCA. As there are many assumptions and limitations in an LCA study, interpretation may not clearly identify a winner, but it provides a better understanding. This phase identifies the significant issues based on the findings of LCI and LCIA by contribution analysis, dominance analysis, or anomaly assessment, and communicates these results effectively. It evaluates the adopted methodology and checks for completeness, sensitivity, and consistency of the results. Based on these analyses, the interpretation step develops a conclusion statement and checks whether the conclusions are in line with the goal and scope of the study, by comparing against predefined assumptions and study limitations that are related to both methodology and data used for the analysis. Further, this phase checks the assessment of data quality by studying mean, variability, and data distributions to determine whether any biases or uncertainty occurred and assesses any uncertainties and the significance of the study. The phase also provides full and transparent disclosure of the results and provides recommendations. After the analysis, should the results not meet the requirements of goal and scope, modifications, and revisions become necessary to ensure that the results are in line with the goal and scope of the LCA study. Hence, LCA can be an iterative process.

Implementation of LCA in Different States. State and highway agencies attempt to incorporate sustainability during roadway network development and rehabilitation. For these goals, a good estimation on life-cycle costs and environmental impacts is an integral step in the highway investment decision-making process. Apart from LCCA, life-cycle assessment is currently used by a number of state and agencies to evaluate energy consumption, emissions generation, and natural resources consumption. Table 4 summarizes the different LCA practices adopted by various states. Appendix C presents details about the LCA approaches adopted by the different states.

Table 4
LCA adopted by different states

State	LCA approach
Washington	Study for Comparative LCA
California	Pilot Study for LCA model
Colorado	Research for Regional LCA model
Illinois	Illinois: Pavement LCA: 1 of 5 LCA modules in the Tollway's Roadway

Comprehensive Evaluation of LCA-based Tools. Different LCA-based tools were developed to measure pavement sustainability. The framework for analysis is different; some analyses quantify the environmental effects due to the pavement life cycle, whereas others quantify both environmental and economic performances. This section explains the framework of the different LCA-based tools.

PaLATE. As a free Excel add-on, Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) evaluates both the life-cycle costs and environmental impacts of different pavement alternatives *[33]*. The software is based on a hybrid life-cycle analysis, i.e., it incorporates I-O LCA data with the information obtained from a process-based LCA. For the analysis, the software requires the input of pavement design, pavement design life, and details on equipment to be used during construction. For economic performance, the tool calculates the net present value; for environmental performance, it quantifies the emissions and leachate information. The tool calculates the emissions of CO_2, NO_x, PM10, SO_2, and CO *[34]*. This tool can be used as a decision-making tool to compare competing pavement alternatives. Due to its flexibility and ease of modification to the user, PaLATE can be used by different agencies and companies *[35]*. This tool has been used as an independent tool to assign ratings in the green rating system.

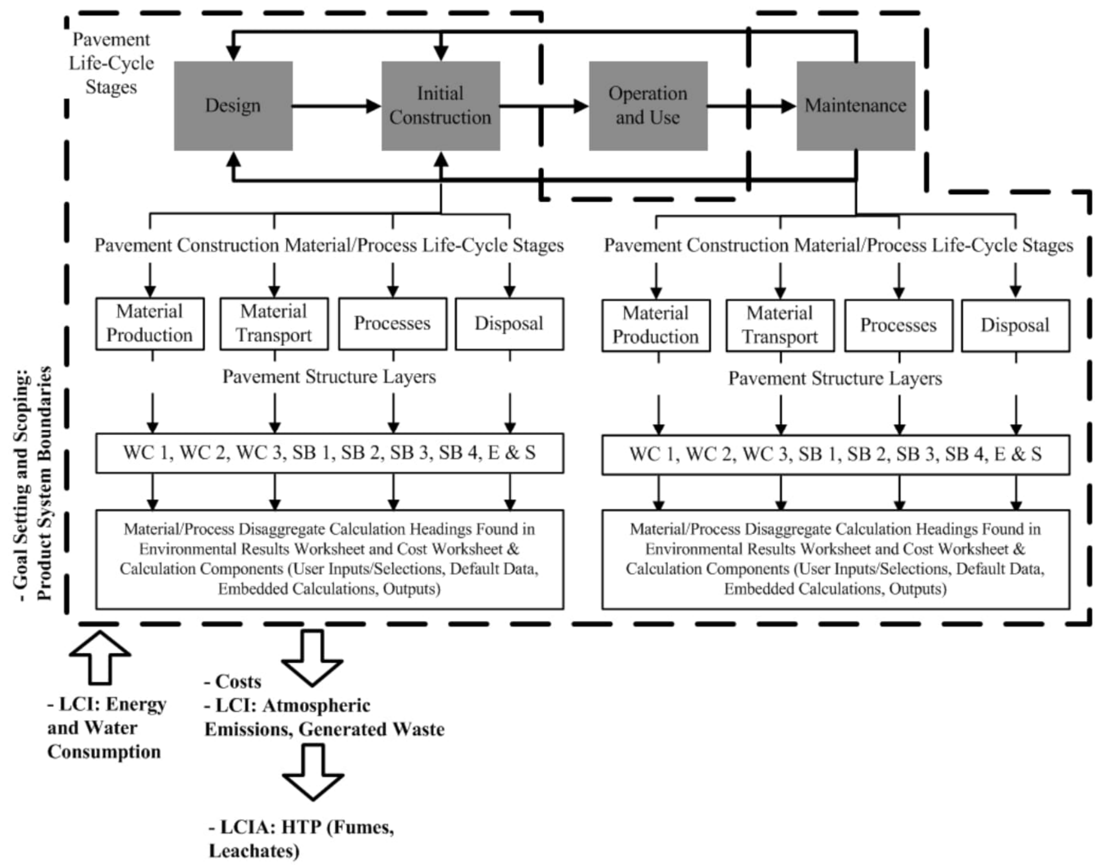


Figure 7
PaLATE LCA product system *[33]*

One of the noted deficiencies of this tool is the utilization of obsolete data, such as using the 1992 I-O-LCA models for the most important environmental calculations. In addition, important factors such as traffic delays and use phase analysis are not considered in the assessment. Carpenter et al. (2007) combined PaLATE with a finite element tool, called HYDRUS2D to assess the environmental impacts of replacing virgin materials with bottom fly ash *[36]*. The researchers concluded that using bottom fly ash instead of virgin materials could enhance sustainability by reducing emissions such as CO, CO_2, NO_x, and SO_2, and water and energy consumption. Although the water flow model indicated that the leached materials were unable to penetrate underground water resources, researchers were reluctant to conclude that there exists no environmental hazard in utilizing bottom fly ash *[37]*.

ROAD-RES. ROAD-RES was developed by the Technical University of Denmark to quantify the environmental benefits of recycling waste materials in construction projects. The LCA based tool quantifies the environmental impacts due to all life-cycle stages of pavement, except the use phase *[38]*. To quantify the total environmental impacts, different impact categories are considered in the tool, such as global warming potential, stratospheric ozone depletion, photochemical ozone formation, nutrient enrichment, human toxicity, acidification, ecotoxicity, and stored toxicity.

The framework of the ROAD-RES model, as presented in Figure 8, shows the resource consumption through the pavement life cycle. The resource consumptions are quantified as consumption of crude oil, natural aggregate, water, natural gas, wood copper, water, and zinc *[39]*.

Birgisdóttir et al. conducted two different studies to implement ROAD-RES into pavements. The two studies showed conflicting results. One research study showed that replacing virgin materials with recycled materials reduces the negative environmental impacts significantly, thereby contributing to pavement sustainability *[39]*. The other study quantified the environmental benefits, due to recycled materials (incinerated wastes) being placed as virgin materials into the pavement subbase. The study concluded that such substitution might cause major environmental impacts.

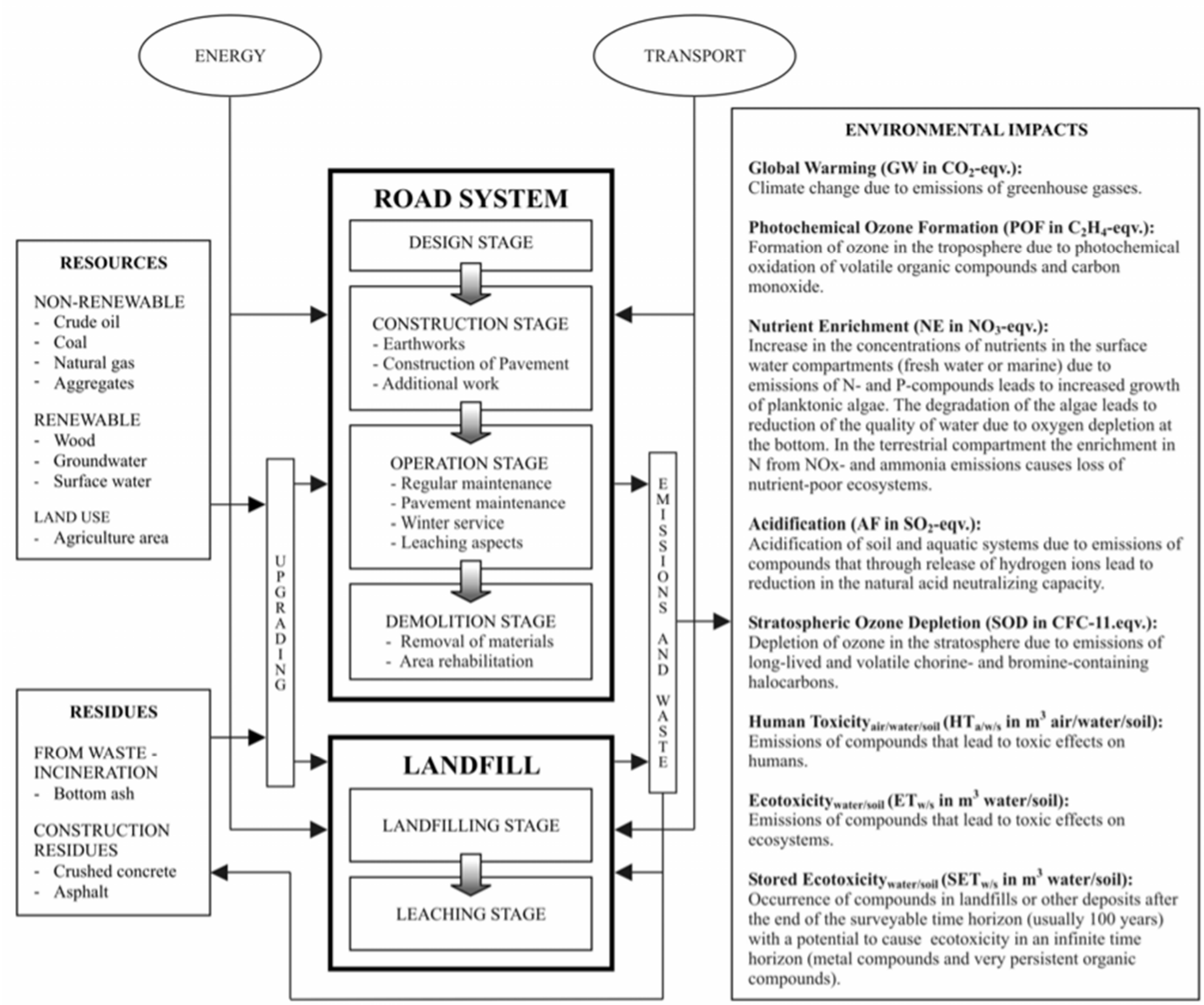


Figure 8
ROAD-RES model *[38]*

ATHENA. The ATHENA pavement LCA, established by the Athena Institute, was developed to quantify the environmental impacts of Canadian and US pavements. The LCA-based software quantifies the environmental impacts associated with materials manufacturing, roadway construction, and maintenance of pavements. The software allows the designers and decision makers to select a suitable roadway design from over 150 pavement designs from the database. The software provides a comparison of the environmental impacts of multiple design options, together with the consideration of a wide range of service lives. The software allows the user to define the pavement design including subbase and base granular materials, and the type of asphalt mixtures (HMA or WMA) from a large equipment and materials database.

To quantify the environmental impacts due to the use phase, the user can input use-phase operating energy and then use the built-in vehicle interaction algorithms, applying the same methodology as the Impact Estimator for Buildings. The inputs required for the analysis involve roadway construction and rehabilitation parameters. As per the input parameters, the software provides the footprint data for environmental impacts by using extensive databases from the Athena Institute and the US LCI database. The environmental impacts are categorized into GWP, AP, human health respiratory effects potential, smog potential, ODP, and EP. Apart from these categories, the software also reports the consumption of fossil fuel and provides a material report, energy and raw material flows, and emissions to air, water, and land as well *[40]*.

DuboCalc. An LCA-based software tool developed by Rijkswaterstaat RWS, Netherlands, quantifies the materials and energy consumed over the entire life of building products, pavements, etc. A list of equipment, process, and materials are connected to the environmental and modeling database. As per the user-defined inputs of different parameters, the tool categorizes the environmental impacts into 11 categories. The performance value of each category is translated into a single number termed the Environmental Cost Indicator (ECI) value. The modeling database and environmental database are the two databases sourced by this software, and are connected to a list of equipment, materials, and processes. It allows the user to input the user-defined parameters and calculates 11 environmental impacts and translating them into a single number, the ECI Value. The lower the ECI value, the better outcome the project is considered to have *[40]*.

Building for Environmental and Economic Sustainability (BEES). The Building for Environmental and Economic Sustainability 4.0, introduced in the late 1990s, integrates a systematic method for selecting environmentally friendly and cost-effective building products *[41]*. The software was developed by the National Institute of Standard and Technology (NIST) for designers and product manufactures for an easy comparison of multiple products or designs. The software encompasses multiple products accompanied by economic and environmental performances. The software quantifies the environmental impacts by adopting life-cycle impact assessment techniques, and measures economic performance using the ASTM International standard life-cycle cost method. All economic and environmental stages of a pavement life cycle are analyzed: raw materials extraction and acquisition, manufacturing, transportation, use, maintenance and rehabilitation, and end-of-cycle. The environmental impacts are quantified into 12 categories. All the categories are normalized and weighted to obtain a single index, which in turn represents the overall environmental performance. Environmental scores are quantified as impact per capita per year; economic performance is a monetary value. Since the environmental impacts cannot be quantified using monetary values, the corresponding score of each performance criterion is then combined into an overall performance score by adopting the Multi-Attribute Decision Analysis (MADA-ASTM standard E 1765). The lowest score indicates the most sustainable alternative, whereas a negative environmental score represents the product as having a beneficial impact on the environment.

PE-2. The Project Emission Estimator (PE-2), an interactive web-based tool, was developed by Michigan Technological University. This tool follows the four stages of LCA, the goal definition and scope of the study, inventory for all energy and material inputs and associated emissions, impact assessment, and interpretation. Based upon the LCA project level and its intended users, contractors and highway agencies evaluate and benchmark the carbon dioxide footprint of highway construction projects. The main purpose of this software is to assist decision makers in selecting the most sustainable products for highway pavement construction. The software allows the user to input different parameters, such as materials and their respective quantities, types, and running hours of equipment usage. However, the software is not targeted for the comparison of pavement alternatives *[20]*. Consideration of carbon dioxide alone, rather than other impact categories in order to quantify environmental impact, limits the usage of this software. The framework of the software is illustrated in Figure 9. The web-based software can be downloaded at http://www.construction.mtu.edu:8000/cass_reports/webpage/.

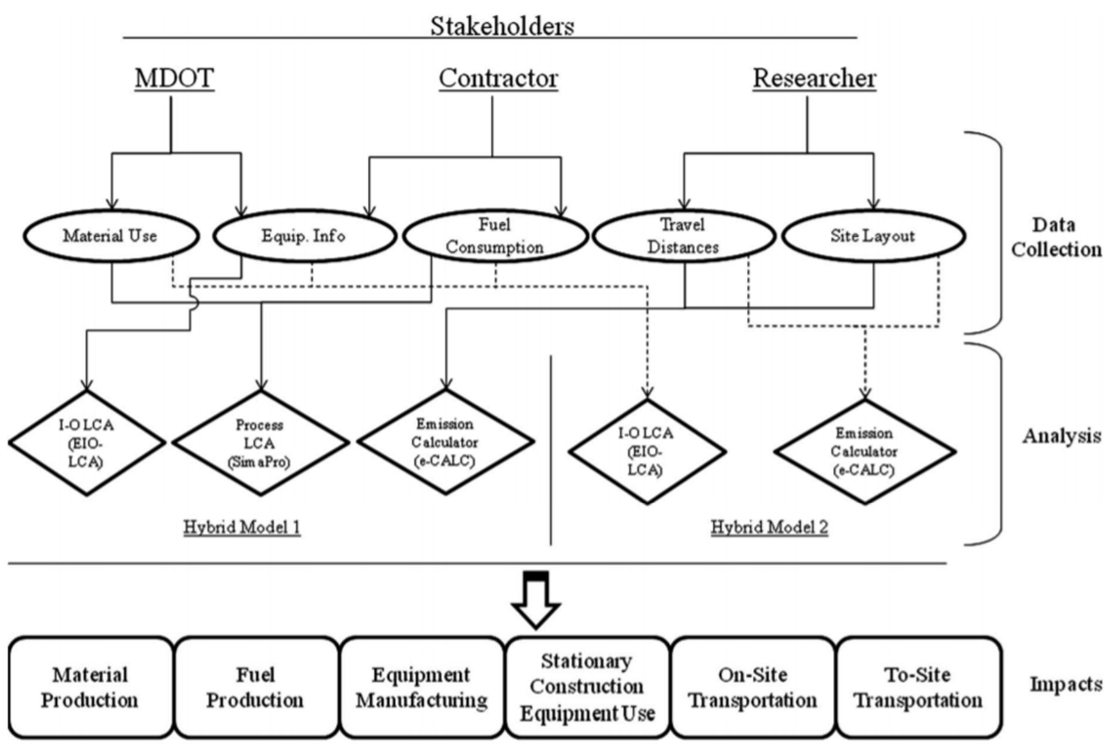


Figure 9
Overview of PE-2 impact estimation process

Limitations of Life-Cycle Assessment. There are many limitations associated with sustainability quantification methods; LCA is no exception. Although it has been the most widely used sustainability quantification tool, there are several deficiencies and limitations associated with LCA. For instance, a time-consuming nature, in tandem with data availability for the data collection process, tend to affect results accuracy. To lessen the data collection burden, secondary source data are preferred. For many secondary data, the methods and assumption made during the data collection procedure are unknown. Since these gaps can create a huge deviation from actual performance, secondary data resources are encouraged only where less accuracy is accepted. Therefore, before conducting a LCA, it is necessary to determine data accessibility, level of accuracy, time and financial resources, and then compare that information with benefits resulting from an LCA analysis to the project *[6]*.

LCA quantifies environmental effects only, and therefore represents a single aspect of sustainability. This cannot be used in a project where the monetary value plays an important role. A comprehensive decision-making process should account for both environmental and economic performances to predict the chosen design or materials that would perform adequately, requiring minimum funds, and causing the least damage to the environment.

A review of past studies, as detailed in Appendix D, shows a variation in LCA results for the same types of pavements and materials. Since standard and defined rule lack for conducting an LCA, there is a deviation in the system boundaries, assumptions, limitations, and interpretation methodologies among different studies. This deviation results in contradicting results for the same types of materials and pavements. This LCA nature limits its application in pavements for comparison of multiple pavement alternatives. Further, a review of past studies indicates that pavement conditions and performance are not considered in the analysis. Hence, for future research, it is recommended that such criteria be considered, and should be integrated in the process of selecting a functional unit. Further, the end-of-life option, including different recycling approaches, should be considered in the future. Together with end-of-life, pavement conditions deterioration should be included in the maintenance and rehabilitation phases for inventory data collection.

In the context of LCIA, region-specific impact categories should be developed to reduce uncertainty. Many designers are unaware of pavement sustainability or performance metrics pertinent to LCCA. LCA and other sustainability metrics should be defined and guidelines established, to collect the required data. As mentioned earlier, most of the past studies focused on GHG emissions. GHG alone does not represent the total impacts related to the pavement system;

hence, a wide range of impact categories, other than energy and GHG emissions, should be considered.

Environment Product Declaration

The comparison between two distinct LCAs is a challenging task, due to variations in the assumptions, limitations, system boundaries, and methodologies adopted among different studies. Environment Product Declaration (EPD), an emerging tool, declares and defines the environmental impacts based on a comprehensive LCA by following a set of standard rules for a specific product/material *[42]*. EPD provides a result that is consistent and comparable. That comparable nature, in tandem with inventory data provided in the EPD, alleviates the burden of data collection procedure. EPD is based on a cradle-to-gate framework and quantifies the environmental impacts associated with raw materials extraction/production, transportation from extraction, and manufacturing of the product. To create a reliable EPD, LCA must meet specific requirements. Information on product modeling, the type of data to be used, and the environmental impact categories to be included, is standardized. To address this matter, respective industries developed the Product Category Rules (PCR) as a systematic protocol to compare identical products of various companies in terms of environmental impacts *[43]*.

For the development of EPD, the hired program operator identifies the reliable PCR, if it exists. If not, the program operator develops a PCR by forming a PCR committee and conducting an LCA. A PCR committee would create a new PCR by filling those required sections and categories, which include defining the (a) product category names, codes, and definitions, (b) the predesignated usage of the resulting EPD developed by PCR, (c) the existing PCRs, (d) the development date, and (e) the period that the EPD is valid. Developed PCR passes through a public review and once finalized, becomes published. Based on the developed/selected PCR, LCA is conducted by an LCA consultant, and EPD is developed. Once developed, EPD goes through a third-party review and verification. After the completion of the review process, EPD is finally published.

EPDs are developed and published either by an individual company/agency, or by averaging the inventory data from different industries. If the data from different companies are aggregated to represent the average cradle-to-gate impact value associated with the product for a certain region, it is termed as an industry average EPD. Such aggregated data may be used as a secondary data source for another company's EPD. If an EPD is developed by a certain company and solely uses its own data, it represents the individual EPD for that corresponding company. As per the United Nations Standard Products and Services Code (UNSPSC) database, there are currently 40,000 EPDs available for different products *[44]*.

The two major types of EPD may be referred to as Business-to-Business EPDs, and Business to Consumer EPDs. Type III EPD, developed for business-to-business communication, creates harmonization among different stakeholders, and provides awareness of different aspects of environmental impacts, related to their products *[45]*. Type III EPD can be used for greener claims for procurement and marketing, and to provide LCA data in the value chain. Another use is in the business-to-consumer communication. Increasingly, consumers demand companies to be transparent and to take responsibilities for the whole supply chain of company products. EPD is based on the life-cycle perspective, and thus can provide comparable and verified results to the consumers. Therefore, EPDs are also suitable for Business-to-Consumer communication. The standard ISO 14025 sets additional requirements on EPDs that are intended for Business-to-Consumer (B2C) communication or are likely to be used by the consumers. B-to-C EPD of a product comes at the end of the supply chain, i.e., cradle to grave, whereas EPDs that are mid-stream in the supply chain will likely be B-to-B (cradle to gate) *[7]*. Irrespective of the purpose of EPDs, the declared unit for a specific product should be the same as stated in the product PCR. For example, for concrete, the declared unit is m^3, yd^3, or ft^3, and for asphalt mix, it is a ton. EPDs are developed for materials and the application of material differs from industry to industry. Since the product has no specific function, it is unreliable to represent the environmental damage in the specific functional unit. As a result, the study that integrates the EPD for environmental analysis should properly state the method of conversion from a declared to a functional unit *[46]*.

It should also be recognized that EPD has some limitations, because it does not address human health toxicity or economic and social impacts, which are costly to develop. However, many different methodologies can reduce the cost of EPD development. One such tool is being developed by the National Asphalt Pavement Association (NAPA). NAPA is creating an automated tool that will aid contractors to develop EPD. The tool requires that the total energy input and fuel consumption, the total water usage from the plant, and the tool results be inputted into an EPD. Such an automated tool is inexpensive and accounts for innovation within the industry.

EPD in Pavement Construction. Recently, stakeholders attempted to identify a process in which to apply EPDs in pavement construction *[47]*. The process would constitute a great advantage, since all the products used in pavement projects would have an EPD certificate. As previously mentioned, EPDs are developed, based on a product category rule. The PCR for Portland and blended cements is provided by the Product Category Rules Task Group and the National Ready Mixed Concrete Association EPD certification for cement and concrete. The developed PCRs were implemented by different concrete mix producers in order to develop an individual EPD and an industry-wide average EPD for concrete products. NRMCA has developed industry-wide or sector average EPDs, based upon ISO 14025 by declaring the environmental characteristics of different concrete products from different climatic zones, which are used for different purposes, such as public construction, as well as residential and commercial constructions *[48]*. This EPD program averaged inventory data from different participating companies to produce an industry-wide average for EPD. For asphalt concrete, NAPA has developed PCRs for asphalt pavement construction *[49]*. NAPA has also developed a EPD tool for North American asphalt mixes in accordance with ISO 14025 and EN 15804. The EPD program developed by NAPA is not publicly available, therefore to date; no EPDs are available for asphalt concrete.

NAPA EPD program and NRMCA EPD Program. The NAPA EPD program is aimed at the development of PCR and Type III EPD for asphalt mixtures and ingredients, while the NRMCA EPD program facilitates the development of a similar product for concrete products and ingredients; both programs intend to address business-to-business and business-to-consumer applications.

For the development and maintenance of PCR, both the NAPA EPD program and the NRMCA EPD program outline a set of instructions, which includes minimum requirements for the following:

- The name and product category;
- Application of the EPD developed using PCR;
- Any existing PCRs;
- Product category definition and description;
- Functional units and/or declared units definitions;
- Allocation and calculation rules;
- Environmental impacts;
- Other life-cycle inventory analysis indicators, and information;
- An accurate description of environmental aspects of the product;
- Goals, scope and application of LCA-based data for the product category;
- Rules on producing additional environmental information;
- Details on life-cycle stages;
- Procedure for inventory analysis;
- Environmental impacts and the way they are collated to be reported in the EPD; and
- The period of validity of the PCR.

The system boundaries defined by NAPA PCR for asphalt concrete is illustrated in Figure 10. Both the programs outline five years as the validity period and require a review after that period.

Compliance with relevant standards is required by both the programs, which include ISO 14020, ISO 14025, ISO 14040, and ISO 14044. The NRMCA EPD program requires ISO 21930, an additional standard, to be followed.

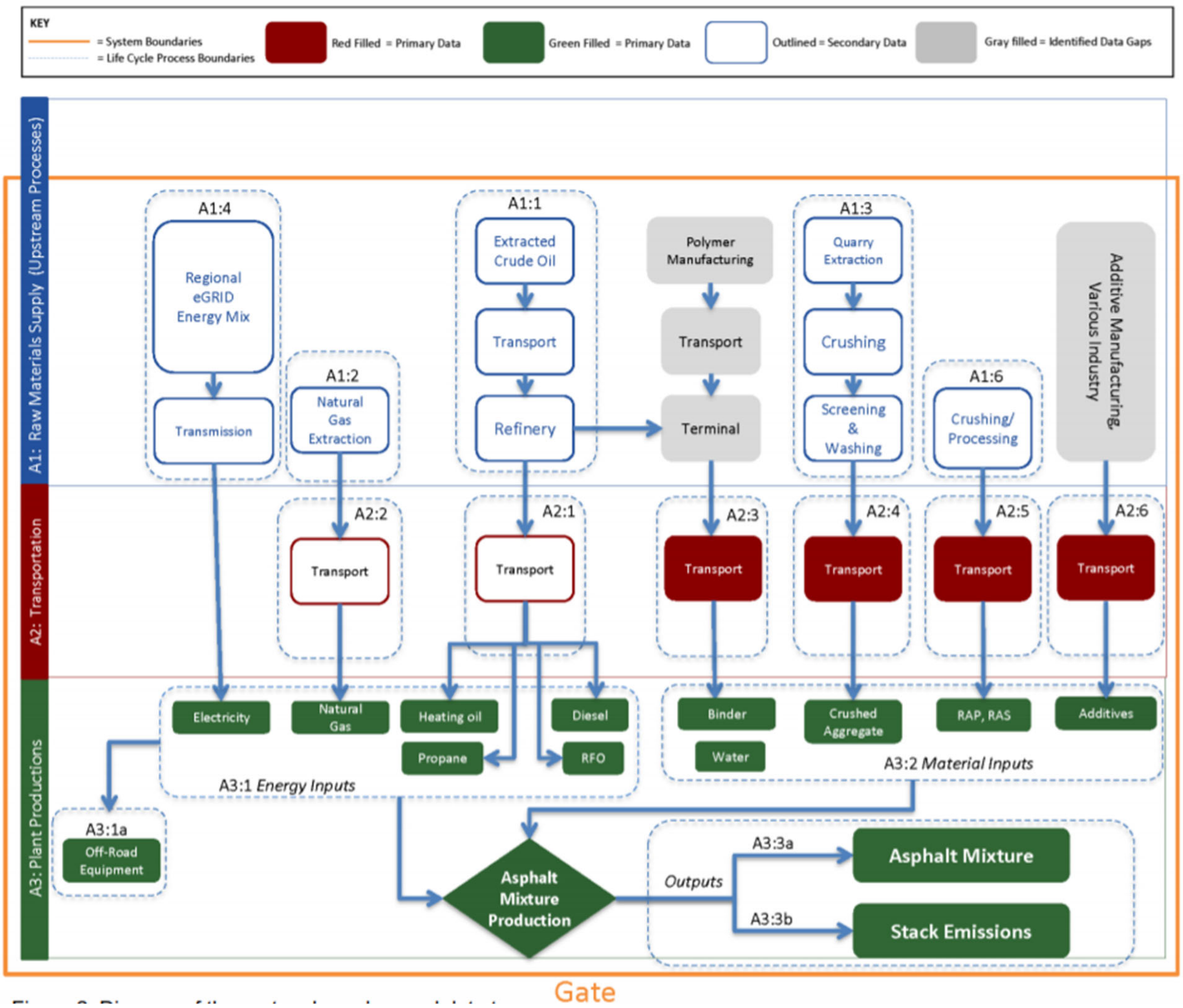


Figure 10
System boundary diagram and data types for asphalt concrete EPD *[49]*

Main Purpose of NAPA and EPD program. The main purpose of creating EPDs for concrete and asphaltic materials is to provide a complete library of environmental data, which are reliable and comparable. This library may be used in pavement projects for future construction. The decision makers are then able to compare different types of concrete and asphalt mixtures, as well as the components of each product, in order to select a mix that leads to sustainability enhancement. Ultimately, the main objective of this program is to develop PCRs and to verify EPDs in a consistent and reliable manner, based on ISO 14025.

NRMCA EPD program has successfully developed PCR for concrete materials and implemented those to develop the concrete EPDs. To date, there are thousands of individual as well as average EPD data for concrete mixes. In the context of the NAPA EPD program, the latest version of draft PCR for the NAPA EPD program was published in June 2016. The major challenges in obtaining the main objective of the NAPA EPD program are (a) defining the declared unit and system boundaries, (b) identifying the availability for high quality inventory data, (c) addressing the missing inventory data, (d) understanding among the upstream supply industries (petroleum refinery), (e) allocation of impacts to the co-products, and (f) reused and recycled materials *[7]*. When these challenges are understood and addressed, then a strong tool in the decision making for procurement, construction, and maintenance will emerge that can be integrated into the current design as well. The comparison of asphalt and concrete products using EPD is not appropriate at this time. NAPA has developed the NAPA Emerald Eco-Label Program to provide a third-party reviewed for asphalt mixes. The tool is not available publicly, and therefore no EPDs are publically accessible for asphalt mixes. Asphalt EPD may be compared to other asphalt-mix EPDs, which were developed with the same PCR. The PCR for two different materials are developed based upon different rules, assumptions, and limitations, and therefore are not currently comparable.

Relationship between LCA, PCR, and EPD. LCA, PCR, and EPD are necessary to evaluate the environmental performance of a product throughout its life cycle, see Figure 11. The PCR defines boundary conditions, data, and system inputs. The rules defined in the PCR are used to evaluate the LCA and to quantify the environmental performances of a product. The EPD then disseminates the outcome of LCA for the public and stakeholders *[50]*. These three elements provide together a detailed assessment of a product's environmental impacts.

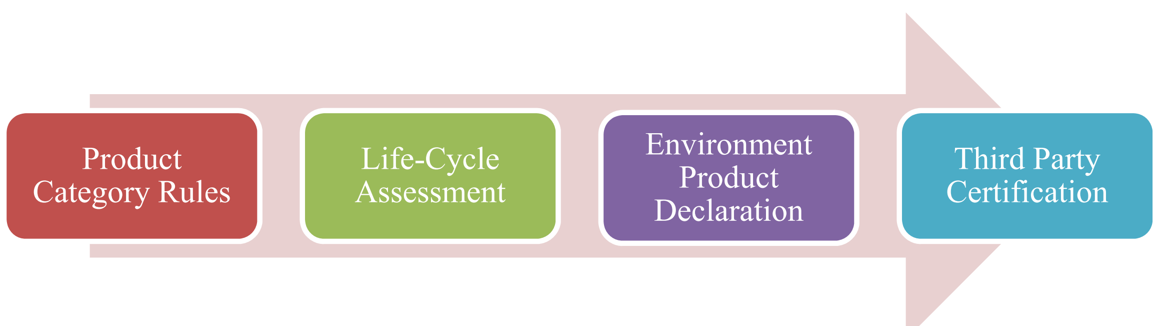


Figure 11
Relationship between LCA, EPD, and PCR

Limitations of Environmental Product Declarations. EPDs have successfully addressed the major limitations of life-cycle assessments. Some of the LCA limitations, such as not accounting for either social or economic impact, still apply to EPD. In addition, most of the published EPD do not include the impact to human health toxicity, due to the data gaps and uncertainty associated with the chosen models. Further, EPD cannot be used for products with differing service life. For example, comparison of a pavement design with a service life of 50 years and another with a 20 years use of EPD is not reliable. Similarly, PCR for asphalt mixes and concrete differs. A comparison between these two pavement types by incorporating EPD is not currently feasible. Lastly, implementing industry average data for environmental impact analysis estimates the average impact and may be less accurate. Hence, before reaching a final decision when using EPD, the above-mentioned limitations should be addressed and properly accounted for, in order to provide reliable results.

Sustainability Practices Adopted by State Agencies

Federal and local policies successfully motivated agencies, stakeholders, and companies to engage in sustainability practices. Despite a national guidance toward sustainable pavement based on federal policies, different DOTs have different policies and specifications with respect to sustainability. Therefore, the level of involvement in sustainability practices varies from state to state.

Generally, most state DOTs have focused on the economic and environmental aspects of pavement sustainability. On the other hand, due to the problems associated with defining and quantifying social sustainability, little attention was given to this component. This section of the report reviews the sustainability practices adopted by different state DOTs.

State Policies and Specifications. According to national transportation guidelines, sustainability practices are not mandated in the US, but environmental instructions exist within the guidance offered by federal agencies, in order to direct the activities of state DOTs. According to the environmental guidance offered by the National Environment Policy Act (NEPA), some planning requirements have been considered by state DOTs *[51], [52]*. FHWA and AASHTO are agencies that offer sustainability guidance.

Many states attempted to implement land use policies in order to improve sustainability; Washington and Oregon are leading this movement. The Transportation Planning Rule (1991) in Oregon State, as well as the Washington State Growth Management Act (1990), are examples of such legislations *[53], [54]*. According to the Oregon Transportation Planning Rule in 1991, the regional transportation growth must be compatible with the state plans designed to satisfy the state transportation development needs. In addition, the Washington State Growth Management Act provides guidelines related to transportation factors and the growth of the transportation system with state development. In addition, states such as Massachusetts, Maryland, Pennsylvania, North Carolina, and Florida implemented land use laws and policies. New Jersey and Colorado are unsuccessful examples of executing land use laws.

The number of activities related to mitigation of GHG emissions increased significantly among the different states. California was one of the first states that adopted laws for GHG reduction. Maryland is another state that decided to implement policies that lead to GHG reduction. The GHG reduction plan in Maryland aims to reduce GHG production by 25% by 2020, in comparison with the amount of GHG emitted in 2006. Florida has a comprehensive plan for Climate Change and Energy consumption, called the Florida Energy and Climate Change Action Plan. GHG reduction practices are part of this plan *[55]*.

State activities have motivated DOTs to move forward, parallel to GHG reduction policies. State policies, such as GHG reduction policies, require agencies to collaborate with one another in order to achieve specific targets and objectives. For example, state policies in Colorado require CDOT to provide a state plan to fulfill state transportation needs by means of alternative solutions, which did not include roadway development *[56]*.

Sustainability Enhancements and Climate Change Considerations. According to EPA requirements and federal transportation legislations, all state DOTs should consider environmental factors. A number of DOTs have designed project development plans; other practices usually can be sorted into two groups: environmental practices or solutions concerned with climate change issues. Table 5 illustrates a summary of states' environmental practices *[56]*.

Table 5
Summary of states environmental practices *[56]*

DOT	Practice	Description
Oregon	Context-sensitive and sustainable solutions	Decision-making framework that combines context-sensitive design with sustainability principles (www.oregon.gov/ODOT/HWY/OTIA/bridge_delivery.shtml)
Delaware and Tennessee	Geographic information system– based environmental screening	Statewide GIS data used to identify environmental issues during the planning process; requires GIS data from multiple state, regional, and local agencies
Florida	Efficient transportation decision-making	Process to anticipate environmental problems early on through partnership with resource agencies, public involvement, and GIS-based environmental assessment (http://etdmpub.fla-etat.org/est/)
Pennsylvania	Linking planning and NEPA	Training program to educate employees on linkages and overlaps between planning and NEPA in order to streamline both processes (www.environment.fhwa.dot.gov/integ/int_pennsylvania.asp)
Vermont	Energy and climate change action plan	Preventive measures to address impacts of air quality and climate change, including both mitigation and adaptation approaches; involves coordination with local governments, state agencies, and neighboring states (www.aot.state.vt.us/Planning/Documents/Planning/VTransClimateActionPlanfinal1.pdf)
California	Climate action program	Active climate change mitigation and adaptation measures in response to state legislation; includes greenhouse gas reduction strategies, sea-level rise assessment and habitat-connectivity study (www.dot.ca.gov/climateaction.htm)
Oregon	Climate change mitigation policies and practices	Efforts to address climate change through both internal and external practices that address vehicle miles traveled and system efficiencies; formed a Climate Change Executive Group and Climate Change Technical Advisory Committee to establish priorities and guide Oregon DOT activities; recognize importance of land use planning and multimodal planning for mitigation (www.oregon.gov/ODOT/SUS/index.shtml)
Illinois	Sustainability program	Initiatives to improve agency's internal sustainability (energy efficiency, emissions reduction, recycling) and be a model for local governments

Several green solutions, such as using vehicles with lower rates of GHG emission, or planting biodiesel corps, have been adopted by different DOTs. Thirty-three percent of state DOTs attempt to improve climate change issues associated with pavement projects. Most of these efforts and initiatives, related to climate change, were due to GHG reduction policies adopted by states or government directives. Vermont and California transportation agency efforts were focused toward comprehensive climate change plans adopted by the state. Recently, Oregon published a plan to mitigate GHG emissions to reduce climate change consequences. During preparation of this plan, the agencies targeted three general goals: (1) halt emission growth by 2010, (2) reduce emissions 10% below 1990 levels by 2020, and (3) reduce emissions 75% below 1990 levels by 2050. An explanation of these practices is presented in Table 5 *[56]*.

OBJECTIVES

The objective of this study was to conceive and develop a decision-making tool for evaluating the sustainability of pavement designs and products, based on a cradle-to-gate analysis. This tool is based on Environmental Product Declarations (EPD) in order to enhance the reliability and consistency of the analysis. It was developed such that it can be integrated with state-of-the-art pavement design methods such as Pavement ME as well as the AASHTO 93 pavement design method. The proposed tool was developed for pavement designers and decision makers such that it could be used in the evaluation of alternative designs and products by optimizing pavement mixes.

SCOPE

The environmental impacts for the adopted system boundaries were quantified by developing a precise and accurate EPD and transportation module. Both modules were developed by using a compiled EPD database and transportation inventory data collected from different data sources. For economic performance, a compiled economic database was developed and used to evaluate the economic performance of pavement alternatives. As a decision-making tool, a Windows-based software was designed, based on the developed methodology. The software has two modes of analysis, benchmarking and product comparison. Using either mode, the software evaluates multiple concrete mixes. Benchmarking provides baseline results by averaging the impact of multiple selected mixes to quantify the total environmental impacts of a design alternative. Product comparison evaluates multiple products for selecting the most sustainable/economic product. Since EPDs for asphalt are not available, the software analyzes the overall performance of rigid pavements only. Once EPDs are available and the database for asphalt materials is updated, the software will be compatible with flexible pavements as well.

METHODOLOGY

The objective of this project was met by developing a cradle-to-gate framework to combine both environmental and economic performances and to predict the sustainability of pavement alternatives. Sustainable pavement considers and balances environmental, economic and social components. This study addressed only the first two components to quantify sustainability, due to research gaps associated with quantifying the social impacts. As presented in Figure 12, the system boundaries for environmental and economic performances included all activities associated with four phases: extraction and acquisition of pavement raw materials; transportation of raw materials; manufacturing and production of pavement mixes; and transportation of mixes to the site location. Apart from these phases, other life-cycle states of pavement may significantly alter environmental and economic performances. Since this study adopted a cradle-to-gate framework, the criterion for analysis is optimization of pavement mix design/product for engineering, environmental, and economic performances.

The environmental impacts for the adopted system boundaries were quantified by developing a precise and accurate EPD and transportation module. The EPD module quantifies the environmental impacts due to the first three phases, while the transportation module quantifies the impact due to the last phase. Both modules were developed by using a compiled EPD database and transportation inventory data collected from different data sources. For economic performance, a compiled economic database was developed and used to evaluate the economic performance of pavement alternatives. The details on the data sources and module are described in the upcoming sections of this report. The two performance factors were combined into a single score in order to represent an overall performance score characterizing the relative difference in performances among the alternatives considered.

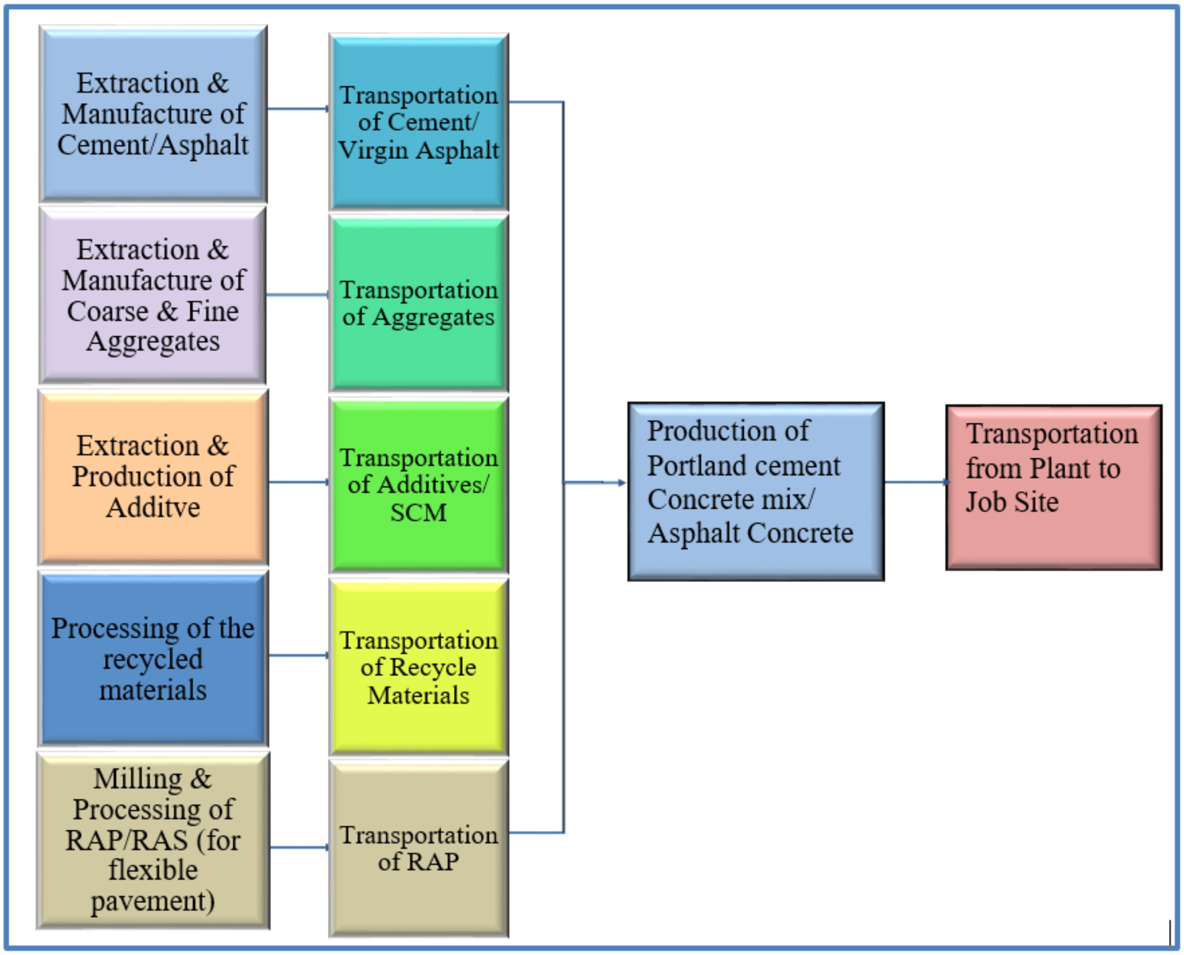


Figure 12
System boundary

EPDs for products with the same PCR are comparable; however, asphalt and concrete have different PCRs−the NAPA EPD program and the NRMCA EPD program, respectively. As a result, a comparison of flexible and rigid pavements is not suitable using the developed framework. Hence, two frameworks−one for each pavement type−were developed in the study. To date, EPDs for asphalt materials are not available to the public. Consequently, the EPD database was developed for rigid pavements only.

As a decision-making tool, a Windows-based software was designed, based on the developed methodology. The software has two modes of analysis, benchmarking and product comparison. Using either mode, the software evaluates multiple concrete pavement designs. Benchmarking provides baseline results by averaging the impact of multiple selected mixes to quantify the total environmental impacts of a design alternative. Product comparison evaluates multiple products for selecting the most sustainable/economic product. Since EPDs for asphalt concrete are not yet available, the software analyzes the overall performance of rigid pavements only. Once EPDs are available and the database for asphaltic materials is updated, the software will be compatible with flexible pavements as well.

Data Sources

The objective of this study was to develop and incorporate a cradle-to-gate sustainability measurement tool into pavement design methods such as AASTHO 93 and MEPDG. The sustainability measurement tool was developed by a rational and methodical technique that would assist in selecting a pavement alternative, which results in an optimum balance between engineering, environmental, and economic performance criteria. Among the triple-bottom-line sustainability components, a social component was not considered, due to data and research gaps for the quantification of impacts on the social component. The systematic technique was developed for both rigid and flexible pavements. Since EPD is not available for asphaltic materials, the developed methodology quantifies only the economic performances for flexible pavements. Once EPDs are available for asphaltic materials, the developed methodology is implementation-ready for flexible pavements as well.

Availability of EPDs for concrete materials, transportation inventory data, and cost values allowed for developing the entire methodology for rigid pavements. For environmental performance, this study adopted a cradle-to-gate framework (i.e., EPDs) to quantify the environmental impacts. The data required for environmental performance were collected from both individual manufacturers and industry wide-average EPDs. For economic performance, this study adopted the same system boundaries as in environmental analysis, i.e., the study considered only materials and initial costs collected from the manufacturers and the Louisiana Department of Transportation and Development (DOTD).

EPD Database

EPD describes the environmental impacts from raw materials acquisition to manufacturing of a product as per the declared unit. As previously mentioned, EPDs for asphalt pavement are not available. Therefore, the developed EPDs consist of the environmental impacts associated with concrete products only. For flexible pavements, only mixes collected from nine districts were compiled into a single database for economic evaluation.

EPD Database for Rigid Pavement

The EPD database for rigid pavement is a compilation of different products collected from both the individual companies and the industry-wide average. Environmental impacts due to each product in the database were quantified as per unit cubic yard volume of concrete. Environmental impacts associated with each product in the compiled EPD database were categorized into six impact categories, as shown in Table 6.

Table 6
Impact categories adopted in study

No.	Impact Category	Reference Substance	Description	Unit
1	Global Warming Potential (GWP)	Carbon dioxide	Increase in temperature due to greenhouse gases	$KgCO_2$-eq
2	Acidification Potential (AP)	Sulphur Dioxide	Affects all ecosystems	$KgSO_2eq$
3	Eutrophication Potential (EP)	Nitrogen	Undesirable shifts in ecosystems	KgN-eq
4	Fossil Fuel Depletion	Surplus Mega Joule (MJ)	Depletion of fossil fuel extraction	MJ-eq
5	Photochemical Ozone Creation Potential (POCP)	Ozone	Ozone formation Potential	KgO_3-eq
6	Ozone Depletion Potential (ODP)	CFC 11	Thinning of the ozone layer	Kg CFC-11-eq

As per the plant location, EPD database was structured into three regional levels: (1) statewide region, (2) southern region, and (3) nationwide region. The number of EPD products collected from the different regions is presented in Table 7.

Table 7
Number of products in concrete EPD database

National Region		**US Southern Region**		**Statewide**	
Location	Number of Products	Location	Number of Products	Location	Number of Products
California	1599	Texas	327	Louisiana	132
Washington	57	Florida	3		
Texas	327	Oklahoma	28		
Florida	3	Louisiana	132		
Oklahoma	28				
Louisiana	132				
Total	2146	490		132	

Nationwide and Southern Region EPDs. All the products in the EPD database, separate from Louisiana, were individual EPDs. Individual EPDs are the environmental declarations submitted by a company to represent the environmental performance of its product. Individual EPDs were collected from manufacturer websites, industry communications, and product data sheets. For the nationwide database, EPDs were compiled into a single database consisting of products from the states of California, Washington, Texas, Florida, and Oklahoma.

Individual EPDs. Individual EPDs were collected from companies and consisted of information on impact values, assigned as per the product identification code/serial number; yet, no information was provided on the mix composition. For the mix design breakdown, companies were contacted to collect mix design data sheets. The mix design data were compiled in a single database, providing detailed information on mix design compositions. The mix design information included (a) Portland cement (lb.), (b) fly ash (lb.), (c) slag (lb.), (d) mixing water (gallons), (e) water to cement ratio, (f) coarse aggregates (lb.), (g) fine aggregates (lb.), and (h) air content (%). Together with the mix composition, information on the mixing weight and density were added to the database. The EPD impact values and mix design composition details were incorporated into the EPD database.

The developed EPD database also included information on the company name, plant location state name, and zip code, mix design details, environmental impacts (categorized into six categories), and energy reporting on (a) total primary energy consumption (MJ), (b) concrete batching water consumption (yd^3), (c) concrete washing water consumption (yd^3), (d) total water consumption (yd^3), (e) depletion of non-renewable energy resources (MJ), (f) depletion of non-renewable material resources (kg), (g) use of renewable material resources (kg), (h) use of renewable primary energy (MJ), (i) hazardous waste (kg), and (j) non-hazardous waste (kg). Since, EPDs are valid for five years after the issued date; the compiled database also provides information on the validity/end of the EPD.

Louisiana EPD. Creating an individual company EPD is not only tedious and time-consuming, but it also requires a huge cost in development. Most companies do not have the expertise to conduct an LCA, and they generally hire a consultant to develop an EPD, which requires a significant amount of funds. No company in Louisiana had formally published an individual EPD, due to the high cost for development, in tandem with scarce knowledge on pavement sustainability. The majority of the companies that had no EPDs chose to participate in an industry-wide average EPD program for concrete materials *[48]*. The Athena Institute explained that industry-wide average data for Louisiana (LA) were developed by compiling the environmental impact/inventory data for Louisiana, together with other southern region states. However, data that solely represented Louisiana could not be found. Therefore, a survey was conducted to assess whether industries/companies measure any type of environmental impacts or inventory of product. The survey found that seven Louisiana-based companies participated in the NRMCA industry-wide average EPD. Among those seven LA companies, five companies with 16 plants were included in the study. These five companies, together with 16 plants, are provided in Table 8.

Table 8
Companies that participated in industry-wide average EPD

No.	Company	Plant Name
1	Angelle Concrete Group, LLC	Denham Springs
2	Angelle Concrete Group, LLC	Westport
3	Angelle Concrete Group, LLC	Zachary
4	Builders Supply Co., Inc.	Forth Street Plant
5	Builders Supply Co., Inc.	Minden Plant
6	Builders Supply Co., Inc.	Natchitoches Plant
7	Builders Supply Co., Inc.	St. Vincent Plant
8	Builders Supply Co., Inc.	Viking Dr. Plant
9	Dolese Bros. Co.	South Choctaw Batch Plant
10	Lafarge North America	Plant 30408-Airport
11	Lafarge North America	Plant 30442-Gramercy
12	Lafarge North America	Plant 30453-Houma
13	Martin Marietta	Cheniere
14	Martin Marietta	Jonesville
15	Martin Marietta	Monroe B
16	Martin Marietta	West Monroe

The format and survey questionnaire are provided in Appendix F. The results of the survey are presented below. The company names are not listed in the survey findings to preserve the privacy of the companies.

- **Company A**: The Company provided a copy of the survey, which they submitted to the NRMCA industry-wide average program. They showed keen interest with their participation in this project, and were willing to provide any other assistance to the researchers. They stated that the main reason for their participation in the EPD was to acquire further knowledge on sustainability, demonstrating an interest to work with the DOTD in order to meet future sustainability goals and needs.

- **Company B**: The Company also showed an interest in the project, but did not provide any specific/individual data due to sensitivity issues. They explained that due to the expensive and time-consuming nature of an individual EPD, coupled with no current mandate for it, no individual EPD has been developed. However, the company stated that they would issue an individual EPD in about a year.

- **Company C**: The Company was concerned about data sensitivity and industry competitiveness. They stated that they had no respective department/personnel to handle these kinds of data.

- **Company D**: Company D provided no information regarding data, as they were highly concerned with data sensitivity issues and industry competitiveness. They stated that they will be issuing an individual EPD soon, but could not provide a timeframe.

- **Company E**: The Company did not disclose any specific data, due to sensitivity issues. They stated that their sole participation was with the LEED credit, and explained that the pertinent information is private and therefore cannot be shared.

From the results of the survey, one can conclude that most of the companies were concerned about sensitivity issues. The main motive for participation in the NRMCA industry-wide average EPD program was for the LEED credit.

The collection of industry-wide average data (inventory data) was followed by a collection of Portland cement concrete mixes for rigid pavement. Since the inventory data were collected solely from Louisiana, mixes were collected only from Louisiana as well. To include every region of Louisiana, nine districts were visited to collect the mixes used in state highway projects. The state highway projects included construction of bridges, culverts, manholes, etc., along with pavements. However, since the study is focused on incorporating sustainability measures into pavement design, only mixes that were used in the construction of rigid pavements were used. A total of 132 pavement mixes for project construction from 2012-2017 were collected. DOTD Specifications for Bridges and Roads (2016) specifies three different types of concrete pavement mixes: B, D, and E. Type B is used for the construction of a new rigid pavement or pavement overlay, and Type E is used for patching rigid pavement. Type D was removed from the 2016 specification of rigid pavements. Since the researchers collected data from state projects older than 2016, Type D was also included in this study. Among the 132 mixes collected from Louisiana districts, 104 mixes were of Type B, 7 mixes were of Type D, and 21 mixes were of Type E. The details of the collected mixes are presented in Table 9.

Table 9
Mix details collected from Louisiana districts

District Name	District ID	Type B	Type D	Type E	Total
New Orleans	02	29	—	3	32
Lafayette	03	9	—	1	10
Shreveport	04	19	—	2	21
Monroe	05	1	—	—	1
Lake Charles	07	—	—	—	—
Alexandria	08	1	7	3	11
Chase	58	—	—	—	—
Baton Rouge	61	20	—	8	28
Hammond	62	25	—	4	29
Total		**104**	**7**	**21**	**132**

The mixes collected from the different districts were available in hard copies and were manually entered into Microsoft Excel to create a working database. The mix design sheets collected from the districts provided information on mix design breakdown, such as the content of concrete mix raw materials (cement, fly ash, slag, coarse aggregate, fine aggregate, water additives, etc.), project proposal ID and name, type of concrete mix (B, D or E), and plant code. All of this information was copied and compiled into a single database with each mix designated by a unique Mix ID. Since the same project could have multiple designs, using the project proposal ID for the analysis was unreliable. The designated mix ID also identifies the specific mix for a specific project.

The collected mix design sheets did not indicate the compressive strength values. The DOTD intranet was initially used to gather the compressive strength values for all mixes. DOTD stores information about projects in multiple databases; therefore, compressive strength values for the majority of mixes could not be found from the DOTD intranet. Since mixes were collected from individual districts, associated districts as well as the concrete manufacturer were contacted to provide the compressive strength values. The DOTD Materials Laboratory was also contacted to provide the compressive strength value for each project. The compressive strength values collected from the above sources consisted of multiple compressive strength values. An average value was calculated to represent the compressive strength of the mix. In this study, the compressive strength was used as the main criterion to define the performance of the rigid pavement design and concrete mix. Therefore, the collection of accurate compressive strength plays a vital role in this analysis. The compressive strength value for the collected mixes ranged from 3,598 to 8,200 psi. The compressive strength value distribution for the Louisiana mixes is presented in Figure 13.

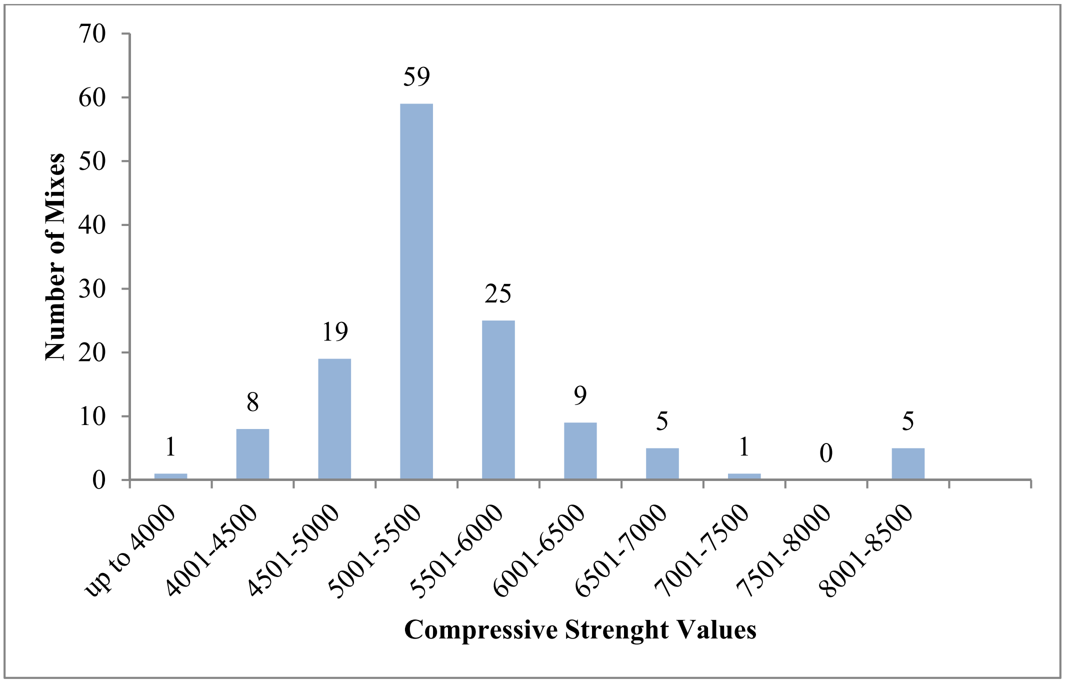


Figure 13
Compressive strength range for Louisiana mixes

The state industry-wide average data collected from the companies, together with mixes collected from the nine districts of Louisiana, were provided to the Athena Institute for development of an industry-wide average EPD for the State of Louisiana. In the context of the Louisiana database, EPD was divided into three stages:

- **A1.** Raw materials extraction;
- **A2.** Transportation impacts from the supplier to the gate of the plant location; and
- **A3.** Manufacturing process impacts.

Flexible Pavement Mix Design Database

Even though EPDs were not available for asphaltic materials, the study developed a framework that would perform as efficiently as rigid pavement when EPDs become available for asphaltic materials. Currently, only the asphalt mix design database was developed by collecting and compiling the mixes collected from the nine different districts. In the future, EPDs will be published for asphaltic materials, and the EPDs for each mix can be updated in order to develop a flexible pavement EPD database. Similar to rigid pavement, mixes were collected from the districts of Louisiana. Apart from the districts, asphalt mixes were also collected from the DOTD intranet database. The DOTD stores information on every project in different databases, some of which are publically available and some of which are not shared with the public. Two hundred thirty-six mixes were collected from both the districts and the DOTD databases.

Rigid pavement collected mix designs were intended only for the top layer since concrete is mostly used in the top layer. For flexible pavement, mixes were collected for both the wearing course and the binder course, as both types are commonly used. Wearing course mixes were further divided into thin asphaltic mixture, conventional asphalt mixture, and Stone Mastic Asphalt (SMA). The collected mixes were also classified as HMA and WMA mixes. The summary of the number of mixes in each category is presented in Table 10. The availability of a wide range of mix designs helps in predicting environmental and economic performances more accurately.

Table 10
Asphalt mix details collected from the nine districts

Layer	**Layer Type**	**Mix Type**		**Total**
		HMA	**WMA**	
Wearing Course	Thin Asphaltic Mixture	6	2	8
	Asphaltic Mixtures	81	107	188
	Stone Mastic Asphalt	7	2	9
Binder Course	Asphaltic Mixture	8	23	31
Total		**102**	**134**	**236**

As in concrete, all the mix designs were available as hard copy, and were inputted into Microsoft Excel. The mix design sheets collected from the districts provided information on (a) volumetric mix design (content of asphalt concrete mix raw materials), (b) binder grade, (c) content and source, (d) air voids, (e) voids in mineral aggregate (VMA), (f) voids filled with asphalt (VFA), (g) nominal maximum aggregate size (NMAS), (h) design level, (i) project proposal ID and name, (j) type of mix, (k) mix use, and (l) additive or antistrip, if any. All of this information was entered into the database, and each mix was assigned a unique Mix ID that is searchable based on mix type, nominal maximum aggregate size, etc.

Transportation Data Source

Transportation is one of the main contributors to environmental impacts. Hence, for any sustainability quantification, it is necessary to include the impacts due to transportation *[57]*. The study developed a simple and rational method to quantify the environmental impacts due to hauling. Environmental impacts due to the transportation of raw materials to plant location are already accounted for in EPD. The transportation module was developed to quantify the total environmental impacts due to the transportation of concrete mixes from the plant location to the construction site. The module was based on transportation average emissions data collected from the United States Life-Cycle Inventory (LCI) database. The US LCI inventory data varies per vehicle and fuel types. In this analysis, three different types of truck: light commercial truck, single unit truck, and combination truck, categorized into (a) light duty truck, (b) medium duty truck, and (c) heavy duty truck as per the Federal Highway Administration (FHWA) was selected. The fuels considered in the transportation impact analysis were diesel and gasoline. The inventory data for each combination of truck type and fuel type were collected. The inventory data were quantified in kg per ton/km traveled for each truck and fuel combination. The inventory data collected for a light commercial truck, diesel powered, are presented in Table 11.

Table 11
Transportation impact value due to light commercial truck, diesel powered *[58]*

Pollutant Emission	Category	Flow Type	Unit	Amount	Remarks
Output					
Ammonia	air/unspecified	Elementary	kg	2.40E-05	
Carbon dioxide, fossil	air/unspecified	Elementary	kg	7.31E-01	
Carbon monoxide, fossil	air/unspecified	Elementary	kg	3.30E-03	
Hydrocarbons (other than methane)	air/unspecified	Elementary	kg	6.51E-04	
Methane	air/unspecified	Elementary	kg	1.47E-05	
Nitrogen dioxide	air/unspecified	Elementary	kg	3.74E-04	
Nitrogen oxide	air/unspecified	Elementary	kg	4.27E-03	
Nitrogen oxides	air/unspecified	Elementary	kg	4.64E-03	
Nitrous oxide	air/unspecified	Elementary	kg	2.91E-06	
Particulates, < 10 um	air/unspecified	Elementary	kg	2.76E-04	PM10 from break wear
Particulates, < 10 um	air/unspecified	Elementary	kg	2.04E-05	PM10 from organic compound, elemental carbon, and sulfate particulates

Particulates, < 10 um	air/unspecified	Elementary	kg	7.50E-06	PM 10 from tire wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	5.35E-06	PM 10 from tire wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	2.68E-04	PM10 from break wear
Sulfur dioxide	air/unspecified	Elementary	kg	1.23E-05	PM10 from organic compound, elemental carbon, and sulfate particulates
Diesel, at refinery	Petroleum and Coal Product	Product	l	2.78E-01	

Economic Data Sources

Using environmentally preferable pavement alternatives is the main solution to reduce the environmental damage associated with pavement systems. Many agencies and stakeholders are concerned with the environmental damage associated with pavement systems, but only a few are willing to pay slightly more to reduce those negative impacts. The sustainability defined in this study considers both environmental performance and economic performance. Therefore, for economic performance, cost data for each product in the EPD database were obtained from two different sources and were then compiled in the cost database. For concrete individual EPD products, the material cost was collected and added to the EPD database. For concrete industry-wide average EPD products, both initial costs and material costs were collected. The material cost was added to the EPD database and for the initial cost, a separate cost database was developed. For flexible pavement, only the initial cost was collected and compiled into a stand-alone database. Material cost is the cost associated with all the processes related to the production of 1 yd^3 volume of concrete or 1 ton of asphalt concrete. On the other hand, the initial cost is the material cost plus cost associated with the transportation of mix to the job site, compaction, laying, overhead, equipment and labor cost of pavement construction. For consistency, all the cost values were stored in the same unit as in the EPD database (i.e., per cubic yard volume of the concrete mix and per ton of asphalt concrete).

Rigid Pavement Cost Data. For nationwide and southern region EPD products, the cost data were collected from the concrete manufacturers corresponding to each EPD product. Since all the products in the EPD database (with the exception of Louisiana products), were individual EPD products, the corresponding company manufactures were contacted to provide the initial mix design cost (material cost) for each product.

For the Louisiana EPD products, the first step was to collect the corresponding concrete mix manufacturer's information associated with each product. The mix design collected from the products contained the mix manufacturer's plant code. The plant code was used to locate the concrete company's name and plant details from the DOTD. After gathering the information for each Louisiana EPD mix, the corresponding manufacturers were contacted to provide the initial material cost. Since all Louisiana products were from state highway costs, the DOTD bid history database, a second source, provided the initial construction cost. For projects with multiple mixes, products were assigned the same initial cost. The initial construction cost data were compiled into a single cost database. Apart from the initial cost, the cost database contains information on project details, project construction year, location and type, contractor names, etc., for each mix. The summary of different data sources is presented in Figure 14.

Flexible Pavement Cost Data. For asphalt materials, the majority of the companies declined to provide the material cost, due to privacy issues. Hence, asphalt materials were assigned with only initial construction costs. Likewise, for concrete materials, the DOTD database was used to find the cost associated with each mix in the asphalt mix database. The initial construction cost data were compiled into a single, separate database. The cost for all asphalt concrete mix was quantified as per ton of asphalt concrete.

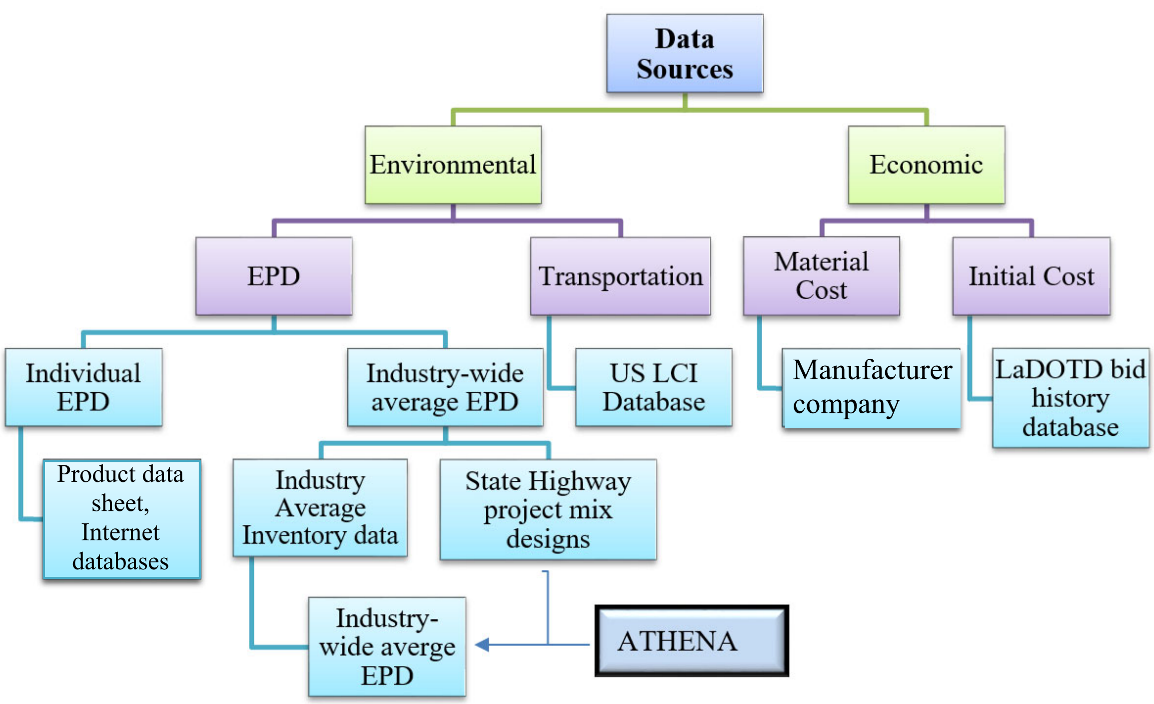


Figure 14
Data sources compilation for concrete pavements

DISCUSSION OF RESULTS

Analysis Framework

Pavement sustainability was quantified by developing a systematic and rational method, which was then incorporated into a pavement design framework to develop the decision-making tool. The methodology for sustainability quantification involves the evaluation of environmental and economic performances, and then to combine both to obtain the overall performance score.

The approach for quantifying sustainability was based upon a cradle-to-gate approach by analyzing pavement alternatives based upon pavement initial design and mix. Since flexible and rigid pavements have different pavement design approaches and mix designs, researchers developed two different frameworks. The main distinction between the two frameworks was in pavement design/mix input. Apart from this, all other processes were the same for the two pavement types.

As illustrated in Figure 15, the environmental and economic performances were analyzed only for those pavement alternatives that met the engineering performance criteria. The performance scores for each criterion were then combined into a single score, referred to as the overall performance score. Finally, the pavement alternative with the least overall performance score is considered the most sustainable/economic pavement.

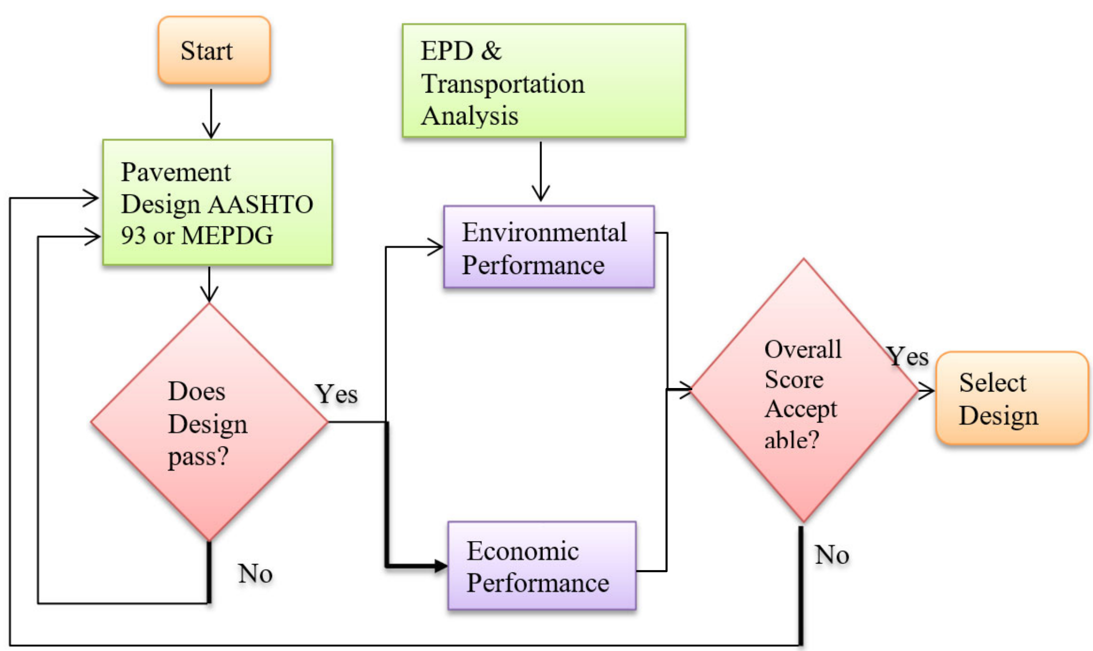


Figure 15
Analysis framework

Environmental Impact Analysis

Environmental impact analysis quantifies the total impact due to production and transportation of pavement materials required for the construction of a one-lane-mile of pavement. Environmental performance was computed based on the EPD module and the transportation module. The EPD module converts the impacts quantified in the EPD database as per declared unit, into a functional unit. The functional unit adopted in this study was the volume in cubic yard (yd^3) per lane-mile. Transportation analysis, on the other hand, computes the impact due to the hauling of pavement mixes from the plant to the job site. In each module, impacts were quantified into six impact categories, which were then combined into a single environmental performance score. The overall environmental performance score represents the impacts to the environment: the higher the value, the higher will be the impact. The impact categories adopted for this study were based on the concrete and asphalt materials PCR, which have specified a mandatory category indicator and a set of inventory metrics to be reported in the EPD of a product. Among those, five category indicators and one inventory metric were adopted in this analysis to quantify the environmental impacts of the pavement mixes. The six impacts adopted in this study are discussed in this section.

Global Warming Potential. The radiation from the sun is absorbed by greenhouse gases (GHG) in the atmosphere, such as water vapor, together with the methane, carbon dioxide, chlorofluorocarbons, and ozone. The presence of these gases reduces the amount of absorbed heat to be re-radiated to space and develops a blanket around the earth's surface, commonly known as the greenhouse gas effect. The emissions generated by different human activities have been increasing the greenhouse effect, resulting in the rise of a global average temperature and leading to the alteration of weather patterns, a rise in sea level, impacts on human health, biodiversity, agriculture, etc. The alteration of weather, sea level rise, and increased temperature has a significant impact on the environment as well as society's infrastructure *[4]*. The burning of fossil fuels, together with the burning of gasoline during vehicle use, and production of limestone are the common sources of GHG emissions. GWP measures the effect associated with the increase in GHG. The impacts of GWP is expressed in terms of grams of CO_2 equivalents; i.e., it measures the amount of CO_2 with the same potential for global warming over a 100-year period.

Acidification Potential. The ongoing decrease in the pH of the Earth's surface due to acidifying agents being deposited on the earth's surface, either by wet process or dry process, is termed as an acidification *[1]*. Acidifying pollutants are generally air pollutants, primarily sulfur and nitrogen compounds, that dissolve into the water or fix into the solid mass, and alters the ecosystem, as well as synthetic system. Acid rain, fossil fuel and biomass combustion are the principal sources of acidification. In the context of pavement LCA, these emissions are dominant in phases where fuels are combusted. For acidification potential, SO_2 equivalents have been adopted as a reference substance *[41]*.

Eutrophication Potential. The process of adding mineral nutrients into the soil and water results in the increase of algae and plants, known as eutrophication. The nitrogen and phosphorus fertilizers used for agricultural production and runoff from livestock operations are the main sources of eutrophication. The increased content of these nutrients causes a loss in biodiversity and the ecosystem imbalance. For aquatic systems, the growth of algae and plants leads to a reduction of dissolved oxygen, therefore causing the death of different aquatic lives. For example, the dead zone in the Gulf of Mexico is due to depletion of the oxygen level *[1]*. For the eutrophication potential, Nitrogen (N) equivalents have been adopted as a reference substance *[41]*.

Ozone Depletion Potential. Stratospheric ozone acts as a filter, since the ozone absorbs all harmful ultra-violet rays (short wave) reaching the earth's surface, and passes only long wave ultraviolet rays. Due to the increase in production of chloroform carbons (CFC), the ozone layer has been depleted. Due to this depletion, the number of harmful rays reaching the earth surface has increased, and can ultimately lead to the increase of skin cancer, changes to the ecosystem, alterations in agricultural production, eye cataracts, and suppression of unsusceptible systems *[59]*. For ozone depletion potential, CFC-11 equivalent has been adopted as a reference substance *[41]*.

Photochemical Ozone Creation/Smog Potential. The emissions from industries are trapped at the ground level, which leads to the formation of smog. With the presence of sunlight, the volatile organic compounds (VOCs) inter-react with nitrogen oxides (NO_x) and produces tropospheric ozone (O_3). The produced ozone can result in a harmful effect to human and other living creatures because the ozone damages living tissue. Since the effect of each pollutant involved in the formation of O_3, joined with environmental conditions, varies as per space and time, a regional/local model may be required to estimate the impacts associated with the formation of smog *[1]*. The common source of smog formation is due to the emissions from traffic use. Exposure to smog can cause chest irritation, respiratory system complications, asthma attacks, and damage to the crops and forests. For smog potential, O_3 equivalent has been adopted as a reference substance *[41]*.

Fossil Fuel Depletion. Apart from the economic impact associated with fossil fuel depletion, there is a growing recognition of environmental impacts due to the fossil fuel depletion. This category quantifies only the impact due to the depletion aspect of the fossil fuel extraction. The impacts associated with the extraction itself is addressed in other impact categories. For quantification of the fossil fuel depletion in North America, the quantification follows the Eco indicator 99 method, i.e., "by measuring the amount of energy required for the extraction of per unit energy for consumption changes over time *[59]*." For fossil fuel depletion, the mega-Joule (MJ) has been adopted as a reference substance *[41]*.

The environmental impact analysis framework was developed for both types of pavements. It needs coherent and precise EPD data for the analysis. Since EPDs are currently available only for concrete mixes, the developed tool evaluates environmental analysis and overall performance of rigid pavements only. However, availability of EPD in the future for asphalt concrete will result in an executable tool for comparison and benchmarking sustainability of a flexible alternative. The EPD analysis for the two pavement types were different; yet, the transportation module was the same. The next section describes the framework for both types of pavements.

EPD Analysis

EPD analysis, a cradle-to-gate system, quantifies the total environmental impacts due to the first three phases of the considered system boundary per volume (yd^3)/lane-mile. The impact value for mixes were also quantified per the declared unit (i.e., yd^3) for concrete and per ton for asphalt concrete. Hence, the primary goal of this analysis was to convert the collected inventory data into the functional unit. Two EPD analysis frameworks were developed to quantify the environmental impacts for each pavement type.

Rigid Pavement Framework. The impact due to production of unit yd^3/lane-mile of concrete mix was quantified in four major steps, as illustrated in Figure 16. For the EPD analysis, the initial step was to define the pavement design/mixes that met engineering performance criteria as determined from MEPDG or AASTHO 93. Since the analysis was based upon the optimization of mixes, the mix whose compressive strength values were within the requirements of the proposed design may be selected. The EPD database encompasses multiple mixes for the same compressive strength value. The criteria for selection of pavement mixes are dependent upon the user/designer experiences and the results of the analysis.

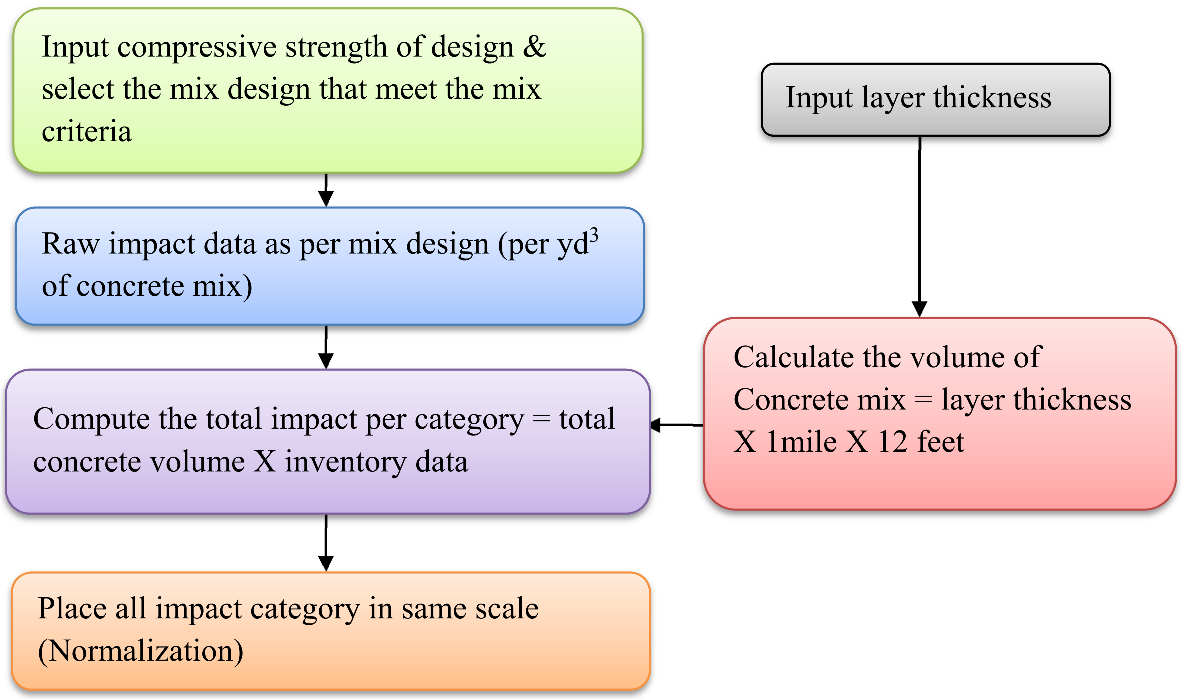


Figure 16
Rigid pavement analysis framework

The process of mixture selection is then followed by the extraction of impact raw data for the selected mixes from the EPD database. In the third step of the analysis, the impact was quantified for each mix selected from the database. Equation (1) shows the computation of the total impact for rigid pavement.

$$\mathbf{T_1 = I_1 x\ 1\ mile\ x\ 1760\ x\ L_1 x\ 0.333\ x\ D_1 x\ 0.02778} \quad (1)$$

where,

T_1= Total impact per each impact category due to the production and transportation of rigid pavement materials, yd^3 per lane-mile;

I_1= Raw impact value for selected concrete mixes extracted from EPD database; for GWP in Kg-CO2/ yd^3;

L_1= Lane width (adopted as 12 ft. in the analysis);

D_1= Thickness of concrete pavement in in.

Equation (1) computes the total impact for each impact category from raw materials extraction to the production of yd^3/lane-mile of concrete mixes. Thus, computed impacts were in non-commensurate units, i.e., GWP represented in $KgCO_2eq$, AP in $KgSO_2eq$, etc. The impact value for each impact category was then converted into a single, common unit by normalization. Reference values developed by the US EPA Office of Research and Development were used to normalize all the impacts into a common scale. The normalized impact values show the performances in terms of US flows per capita per year. The normalization factor for the different impact categories is shown in Table 12.

Table 12
EPA-recommended normalization factor

Impact Category	Normalization Values
GWP	24000
AP	0.16
EP	91
ODP	22
POCP	1400
Fossil Fuel Depletion	288572.50

Flexible Pavement Framework. The difference between the rigid and the flexible pavement frameworks was due to the difference in the pavement design/mix. Compressive strength was used to define the performance of the rigid pavement, but for flexible pavement, no single criterion defines the overall performance of the mix. Therefore, the developed framework, as presented in Figure 17, allows the user to select a mix from the mix database that meets the Superpave design criteria and specifications of the proposed project. As in the rigid pavement framework, the raw impact values for the selected mix design were converted to the total impact as per the functional unit. The volumetric design of asphalt concrete is defined per ton (2000 lbs.) of asphaltic mixture. Equation (2) was used to quantify the total impact for each category. The computed impact for each impact category was normalized into the same unit as the rigid pavement.

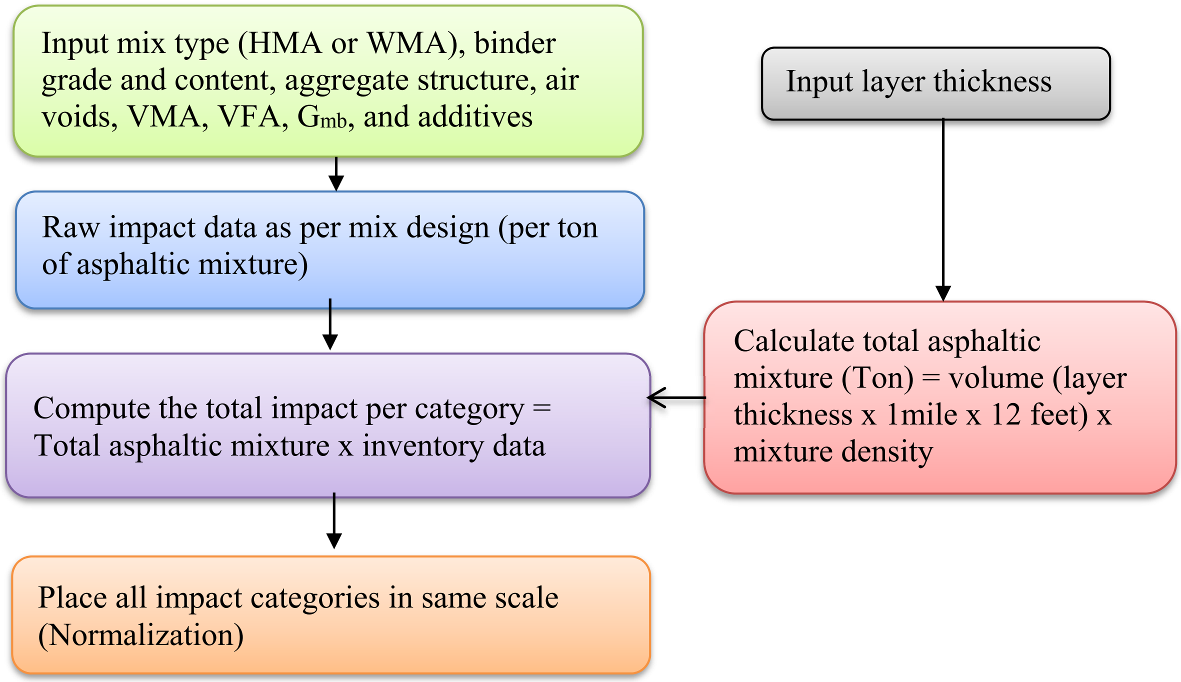


Figure 17
EPD framework for flexible pavement

As in the rigid pavement framework, the raw impact value for the selected mix design was converted to the total impact as per functional unit. Equation (2) was used to quantify the total impact for each category. The computed impact for each impact category was normalized into the same unit as the rigid pavement:

$$\textbf{Total Impact } \mathbf{T_2} \textbf{ (ton per lane mile)} = \mathbf{I_2 \text{ x } T_W} \tag{2}$$

where,

I_2= raw impact value for selected asphalt mixes extracted from EPD database; for GWP in Kg-CO_2/ton;

T_w= Total weight of asphalt mixture in ton; computed by equation (3):

$$T_w = 1 \text{ mile x } 1760 \text{ x } L_1 \text{x } 0.333 \text{ x } T_2 \text{ x } 0.02778 \text{ x } 0.8424 \text{ ton/yd}^3 \text{ x } G_{mb} \tag{3}$$

T_2= Thickness of flexible pavement;

G_{mb}= specific gravity of the selected mix;

Note that 1760, 0.333, 0.02778 are the conversion values to convert mile, ft., and in. to yard, respectively.

Impacts of Transportation to Site

EPD analysis computes the environmental impacts associated with the first three phases of the system boundaries considered in this study. A transportation analysis module was developed for the computation of impacts due to the last phase, which was the transportation of mixes from the plant to the job site. For the State of Louisiana, the impacts calculated from this stage were added to the transportation phase of EPD analysis to represent the total impact due to both phases. The environmental impacts due to transportation are analyzed in multiple steps, as illustrated in Figure 18.

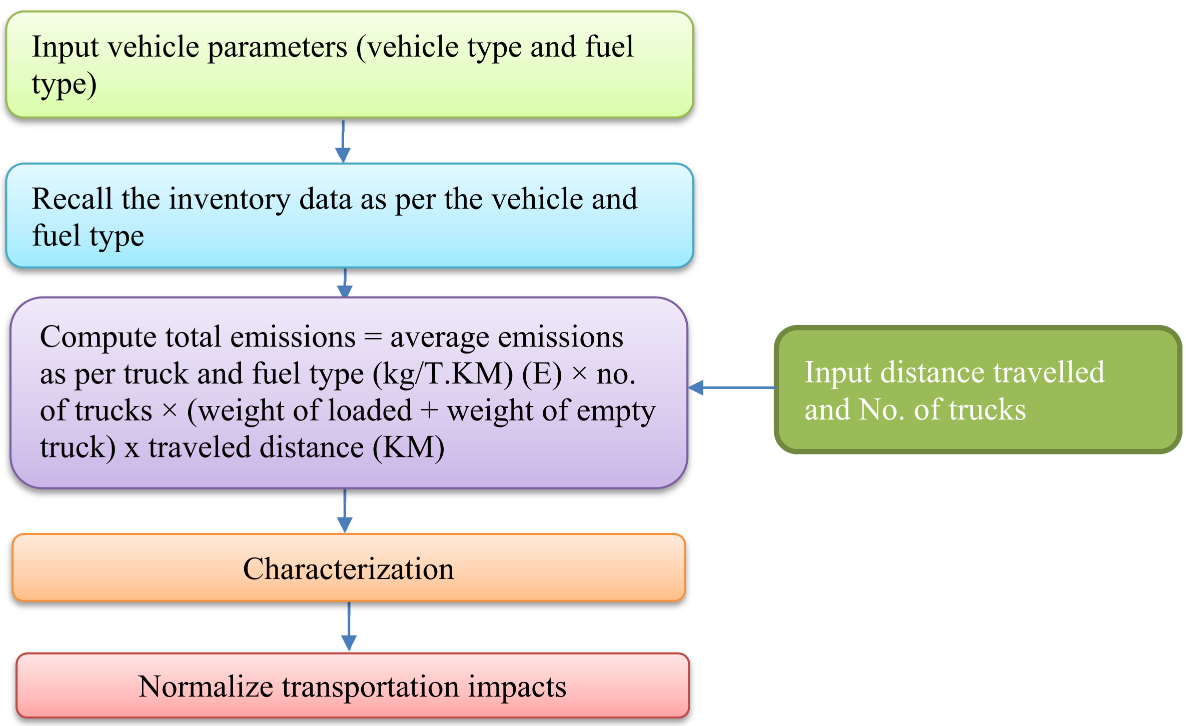


Figure 18
Transportation impact analysis framework

As previously noted, the collected inventory data from the US LCI database vary with truck types and fuel types. Therefore, the initial step for computing the environmental impacts was to define the vehicular and fuel characteristics. In the defined vehicular characteristics, the average emission values were obtained from inventory data and converted to the total emission for each pollutant emission by using equation (4). Equation (4) provides the emission value attributed to the vehicle transportation for both ways, i.e., a principal haul and back-haul. In equation (4), W_{empty} accounts for the empty weight of the truck during the back-haul travel. Depending on the selected mix and type of vehicle, the number of trucks (N) is computed by equation (5). The distance traveled (D) depends upon the plant and construction site location.

$$\mathbf{T= E\ x\ N\ x\ D\ x}\ (\boldsymbol{W_{loaded}} + \boldsymbol{W_{empty}}) \tag{4}$$

where,

T = Total emission; for carbon dioxide in $KgCO_2$;

E = Average emission per truck and fuel type from US LCI database (kg/ T.km);

W_{loaded} = Total weight of loaded trucks (ton);

W_{empty} = Total weight of empty trucks (ton);

N = Number of trucks;

$$N = \frac{\text{Pavement materials required per functional unit } (\text{yd}^3 \text{per lane−mile})}{\text{Load carrying capacity of truck}} \tag{5}$$

D = Distance traveled.

Equation (4) computes the total scale of impact for each pollutant emission. The contribution of emission to each impact category varies. For example, when carbon dioxide is emitted from the vehicle, the amount differs, contributing to the global warming potential and acidification. Therefore, to convert these emissions into equivalent impact categories, characterization is needed. Characterization identifies and quantifies the relationship between the environmental impact and LCI results by defining how much each emission contributes to each impact category selected in the study. This is accomplished by adopting a proper characterization model, which derives characterization factors as a value that represents how an emission relates to each impact category. This study adopted US EPA tools for reduction of chemical and other environmental impacts (TRACI) characterization model. This model was built specifically for the US; therefore, the model consists of region-specific or national average characterization factors. Table 13 presents the characterization factors for each impact indicator selected for this study. As shown in Table 13, each emission factor does not show the same contribution to each impact indicator. For the global warming potential, 1 kg of CO_2 emission contributes 1 kg of global warming potential; whereas, methane contributes 25 times more than carbon dioxide to the global warming potential.

Table 13
Characterization factor

Substance Name	Global Warming Air (kg CO2 eq / kg substance)	Acidification Air (kg SO2 eq / kg substance)	Eutrophication Water (kg N eq / kg substance)	Ozone Depletion Air (kg CFC-11 eq / kg substance)	Smog Air (kg O3 eq / kg substance)
Ammonia	0.00E+00	1.88E+00	7.79E-01	0.00E+00	0.00E+00
Nitrogen Dioxide	0.00E+00	7.00E-01	2.91E-01	0.00E+00	1.68E+01
Nitrogen Oxides	0.00E+00	7.00E-01	2.91E-01	0.00E+00	2.48E+01
Nitrous Oxide	2.98E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Methane	2.50E+01	0.00E+00	0.00E+00	0.00E+00	1.44E-02
Carbon Dioxide	1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Carbon Monoxide	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.56E-02
Sulfur Dioxide	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00
PM10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PM2.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sulfur Oxides	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00
VOCs	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.60E+00

The characterization factor from the TRACI model is multiplied by the corresponding emission mass to compute the total impact of each category. Equation (6) shows a characterization model to compute the environmental impacts related to the global warming potential:

$$\text{Global Warming Index} = \sum \mathbf{m_i} \ \mathbf{X} \ \mathbf{GWP_i} \tag{6}$$

where,

Global warming index = a scaled index expressing the global warming potential of a product;

m_i = mass in grams of inventory emission flow i; and

GWP_i = global warming potential conversion factor from one gram of inventory flow i to CO_2.

The pollutant emission data collected for vehicle and fuel combinations from US LCI were synthesized with the TRACI characterization factors by using equation (6). The values obtained for each impact category for different vehicles and fuel types are shown in Table 14.

Table 14
Transportation impact assessment

Vehicle type	Fuel type	Global Warming Air (kg CO_2 eq / kg substance)	Acidification Air (kg SO_2 eq / kg substance)	Eutrophication Water (kg N eq / kg substance)	Ozone Depletion Air (kg CFC-11 eq / kg substance)	Smog Air (kg O_3 eq / kg substance)	Fossil Fuel Depletion (MJ)
Light duty	Gas	5.52E-01	1.42E-03	5.85E-04	0.00E+00	5.10E-02	7.79E+00
	Diesel	7.32E-01	3.57E-03	1.48E-03	0.00E+00	1.24E-01	1.07E+01
Medium duty	Gas	2.61E-01	7.56E-04	3.12E-04	0.00E+00	2.77E-02	3.69E+00
	Diesel	2.63E-01	1.04E-03	4.31E-04	0.00E+00	3.59E-02	3.83E+00
Heavy duty	Gas	8.56E-02	5.49E-04	2.27E-04	0.00E+00	2.09E-02	1.23E+00
	Diesel	9.22E-02	4.30E-04	1.78E-04	0.00E+00	1.48E-02	1.34E+00

The computed environmental impacts for each impact category were then normalized into fixed US scale impact values as in the EPD analysis.

Overall Environmental Performance

The EPD analysis and transportation analysis computed the environmental impacts due to the first three and last phases of the considered system boundaries, respectively. To evaluate the total impact scores for each category, the normalized values from both analyses were added to compute the relative impact score for each impact category. For example, equation (7) shows the computation of the total impact score for global warming potential. The total normalized scores for the impact score were added in equation (8) to obtain the overall, normalized, environmental performance:

$$\textbf{Total GWP } (\mathbf{GWP_T}) = \mathbf{GWP_{EPD}} + \mathbf{GWP_{Transportation}} \quad (7)$$

Overall Normalized Environmental Performance= GWP_T + $POCP_T$ + AP_T + ODP_T + Fossil Fuel $Depletion_T$ + EP_T (8)

In addition to the normalization values, the study adopted a weighting method for the impact assessment. Weighting is the method of converting normalized impact values from different impact categories by using a numerical value, thus reflecting the relative importance of each category. The weighting factors are dependent upon the value choices, and therefore are not scientifically based. As they are dependent upon the value choices, the weighting results may be different for the same impact indicator values. This study adopted a different set of values to reflect the relative importance for the Department. Based on the selected set of weighting factors, the normalized impact indicator values were multiplied by the weighting factors of the corresponding impact indicators to obtain the weighted impact indicator scores. As illustrated in Figure 19, the overall environmental score was obtained by adding all the weighted impacts scores for each category.

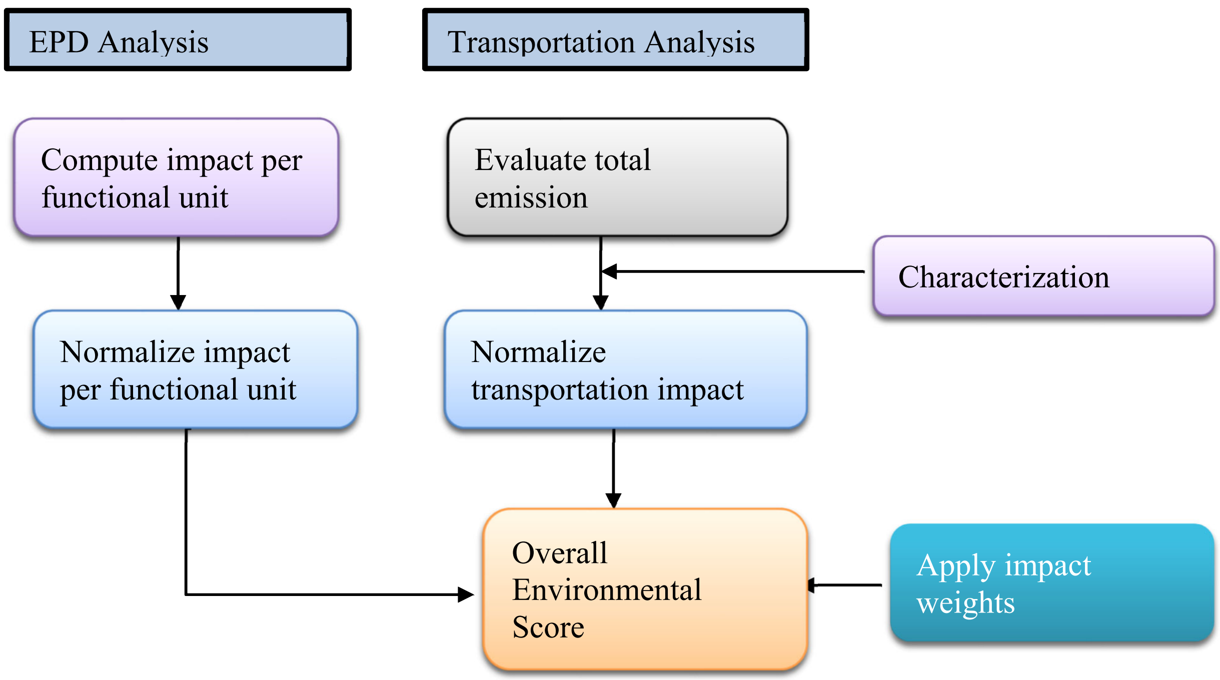


Figure 19
Overall performance analysis

The adopted weights were inclusive of the BEES stakeholder panel, the EPA science advisory board, a set of default weights, and user-defined weights. The perception of relative weights varies as per the society and the user; therefore, user-defined weights allow one to input the relative weights as per the value choices. The EPA science advisory and BEES stakeholder panel judgment consists of 12 and 13 different impact indicators, respectively. Since the study does not consider all those impact categories, the set of weights were adjusted for the six impact indicators considered in this study. Table 15 presents the different sets of weight adopted in the developed tool. The selected set of weights for the EPA science advisory board study and the BEES Stakeholder Panel's structured judgments (2006) are discussed in the sections below.

EPA Science Advisory Board Study. The EPA's Science Advisory Board (SAB) developed a set of weights representing the relative importance of different environmental impact categories in order to allocate resources effectively, the 11 sets of weights were developed based upon the degree of exposure, geographical scale of the impact, and severity of hazards *[59]*. Out of those 11 categories, five categories have been adopted in this study. The study did not consider fossil fuel depletion as an impact. The verbal relative ranking of the risks, such as high-level risk, medium-level risk and low-level risk, were converted into equivalent numerical importance value by adopting the Multi-Attribute Decision Analysis (MADA) method, termed the Analytic Hierarchy Process (AHP) *[41]*. Following the AHP approach and a pair wise comparison, all considered environmental impact categories were assigned a numerical relative importance value. Based on previous experiences with the AHP approach, pair wise comparison values were assigned to each verbal and relative ranking. The Building for Environmental and Economic Sustainability (BEES) project in 1994 converted these pair-wise comparison values into numerical importance values for sixteen environmental impact categories with fossil fuel being included as an environmental impact category *[41]*. The relative importance weights computed for the BEES software were then adjusted into the six categories considered in this study. The standard importance weights and the adjusted weights are presented in Table 16.

BEES Stakeholder Panel Judgments. The conversion of the SAB verbal ranking into a numerical importance value was based upon different assumptions and limitations. Therefore, to develop a systematic and more direct approach, the National Institute of Standards and Technology (NIST) organized a volunteer stakeholder panel meeting in May 2006. A total of 19 individuals (7 users, 7 producers, and 5 LCA experts) participated in the panel. The relative importance weights were computed based upon the AHP process, by initially weighting all impact categories into three-time horizons, i.e., short-term (0 years to 10 years), medium-term (10 years to 100 years), and long-term (> 100 years). The comparison was made with the impact of each category in terms of one year's worth of US flows against their environmental performances. The time horizons were synthesized based upon the voting interest, with all panelists being assigned equal importance and assuming weights of 24%, 31%, and 45% for the short, medium, and long-term times, respectively *[41]*. Thus, a developed set of weights reflects the perception of stakeholders of different combinations. The developed set of weights from the voting interest and time horizon are shown in Table 16. The adjusted set of weights for the six impact categories considered in this study is also presented in Table 16.

Table 15
Weights adopted for environmental impact categories *[41], [60]*

Impact Category	BEES	EPA	Default	User Defined	Normalization Values
GWP	37	25	20	Specified by user	24000
AP	10	15	15		0.16
EP	13	15	15		91
ODP	10	15	15		22
POCP	12	15	15		1400
Fossil Fuel Depletion	18	15	20		288572.50

Table 16
Standard and adjusted weights of EPA science advisory board and BEES stakeholders panel *[41]*

Impact Category	EPA's SAP		BEES stakeholders Panel	
	Standard Weights	Adjusted Weights	Standard Weights	Adjusted Weights
GWP	16	25	29	37
AP	5	15	3	10
EP	5	15	6	13
Fossil Fuel Depletion	5	15	10	18
Smog	6	15	4	12
ODP	5	15	2	10
Indoor Air Quality	11		3	
Habitat Alteration	16		6	
Water Intake	3		8	
Criteria Air Pollutants	6		9	
Ecological Toxicity	11		7	
Human Health (Cancerous Effect)	11		8	
Human Health (Non-Cancerous Effects)			5	

Economic Analysis

The economic performance of a pavement alternative was analyzed using the cost data collected from the different sources. As in the environmental analysis, the economic analysis was based on the cradle-to-gate framework. Even though maintenance and rehabilitation play a vital role in the economic analysis, the framework for the economic analysis for apple-to-apple comparison was adopted to be the same as the environmental impact analysis. Availability of cost data, coupled with well-established guidelines, resulted in a more straightforward economic analysis than the environmental analysis. For rigid pavement, two different methodologies, for individual EPD and industry-average EPD, were established to evaluate the economic performance. For flexible pavement, the cost data were collected only from a single source, and hence the economic analysis framework was the same for all products.

Rigid Pavement. The cost data for individual products were collected from the manufacturers; the data represents the material cost. The collected cost data were then added to the developed EPD database, so that each product in the EPD database was assigned a material cost. The economic performance of individual EPDs can be performed in a single step, by extracting the material cost associated with the selected products from the EPD database.

Industry-wide average EPD products, i.e., Louisiana products, consisted of two different cost values. The first one was the material cost collected from the manufacturer; whereas, the other was the initial construction cost, collected from DOTD cost bid history database. Therefore, for each Louisiana product, both the material cost and initial cost are defined. Even though both costs were available for the Louisiana products, only the initial construction cost was considered for economic performance analysis, as it accounts for equipment, material, labor overhead costs, etc. The material cost for Louisiana products was determined by extracting the material cost corresponding to the selected mix from the EPD database. For economic performance, the initial step was to convert the cost, quantified in the database per declared unit, into the cost as a functional unit. Equation (9) was used to convert the cost quantified per unit volume to total cost per functional unit:

$$\mathbf{C_1 = i_1 \text{ x } 1 \text{ mile x } 1760 \text{ x } L_1 \text{x } 0.333 \text{x } T_1 \text{x } 0.027778} \quad (9)$$

where,

C_1 = Total initial cost ($/yd^3 lane-mile);

i_1 = Initial construction cost for selected mix from the database ($/yd^3);

L_1 = Lane width (12 ft. assumed in this study); and

T_1 = Thickness of rigid pavement.

As previously noted, the mixes (products) collected from the state highway project were constructed at different times. The construction years of each mix were included in the cost database. Considering the time value of money, the initial costs available in the cost database were converted into the present value, using equation (10):

$$\mathbf{P = C_1(1 + r)^n} \tag{10}$$

where,
P = Present value of the considered pavement alternative;
C_1 = Total initial cost of the considered pavement alternative from equation (9);
r = Discount rate; and
n = Difference in years between the construction year and starting year of the proposed project.

The discount rate used in the above equation varies as per the location and as per the yearly cycle. Since the present value was calculated for Louisiana products only, a discount rate of 2.2% for the 12 months ending in April 2017, as published by the US Department of Labor, was adopted in the state product analysis *[61].* The present value calculated from equation (10) represents the economic performance score of the pavement alternative. The lower the economic performance score, the most cost-effective is the design/product.

Flexible Pavement. The cost data available for flexible pavement was only from the DOTD database, i.e., initial construction cost. The initial construction cost for each product was quantified as per ton of asphaltic mixture. Since the functional unit adopted in this study is ton/ lane-mile, the first step was to calculate the total asphaltic mixture required for the construction of a one-lane-mile of flexible pavement for a given thickness. Using equation (3), the total asphaltic mixture quantity was computed as in the environmental analysis. This step was followed by extracting the initial cost of the corresponding mixture from the cost database and computing the total cost by using equation (11). As in rigid pavement, initial costs assigned to the mixes in the cost database were categorized per the construction year of the corresponding project. Using equation (10), the total initial constructed cost calculated from equation (11) was changed to the present value by using an discount rate of 2.2%:

$$\mathbf{Total\ Cost\ (C_2) = T_w\ x\ i_2} \tag{11}$$

where,
C_2 = Total initial cost ($/ton lane-mile);
i_2 = Initial construction cost for selected asphalt mix from database ($/ton); and
T_w = Total weight of asphaltic mixture calculated from equation (3) (ton).

Overall Performance Score

The overall performance score combines both environmental and economic performances of the considered pavement alternative. To compute the overall performance, the computed environmental and economic performance scores were converted into a single score, as illustrated in Figure 20. Both performance scores were computed in two different units, with the environmental performance in impact values per capita per year and the economic performance in \$ per volume (yd^3) lane-mile. Hence, the initial step was the conversion of each performance into a common scale. The relative scale for both performances was evaluated based on the ASTM standards for conducting Multi-Attribute Decision Analysis (MADA), which in turn characterizes the comparison of different attributes *[62].* As presented in Equations (12) and (13), the respective economic and environmental scores for each alternative were computed by dividing the overall corresponding score of each alternative by the sum of corresponding scores for all alternative products/designs considered in the analysis. This would result in a performance score of the economic and environmental factors of each alternative on a relative scale ranging from zero to 100.

By using equation (14), the two scores were then combined into an overall score by weighing both environmental and economic performances by relative importance, and thereby taking a weighted average. As there is no standard weighting recommendation, this calculation is based on the values and perspectives of each manufacturer/designer and/or consumer. The computed overall score represents the sustainability of the pavement alternative, where the lowest score represents the most cost-effective and environmentally friendly alternative. The range of acceptable overall scores depends upon DOT specifications. Currently, DOTD has specified no range of acceptable score and therefore, an equal weight was assigned for both environmental and economic scores.

$$\mathbf{E_1} = \frac{(\text{Weighted or Normalized impact of specific alternative})}{(\text{Sum of weighted or normalized impact of all alternatives})} \text{ x } \mathbf{100} \quad (12)$$

$$\mathbf{E_2} = \frac{\text{Total cost of specific alternative}}{\text{Sum of cost of all alternatives considered}} \text{x}\mathbf{100} \quad (13)$$

$$\text{Overall performance score} = \text{E1 x W1} + \text{E2 x W2} \quad (14)$$

where,

E_1 = Relative environmental performance score;

E_2 = Relative economic performance score;

W_1 and W_2 = the relative weighting of environmental impact and economic value, respectively.

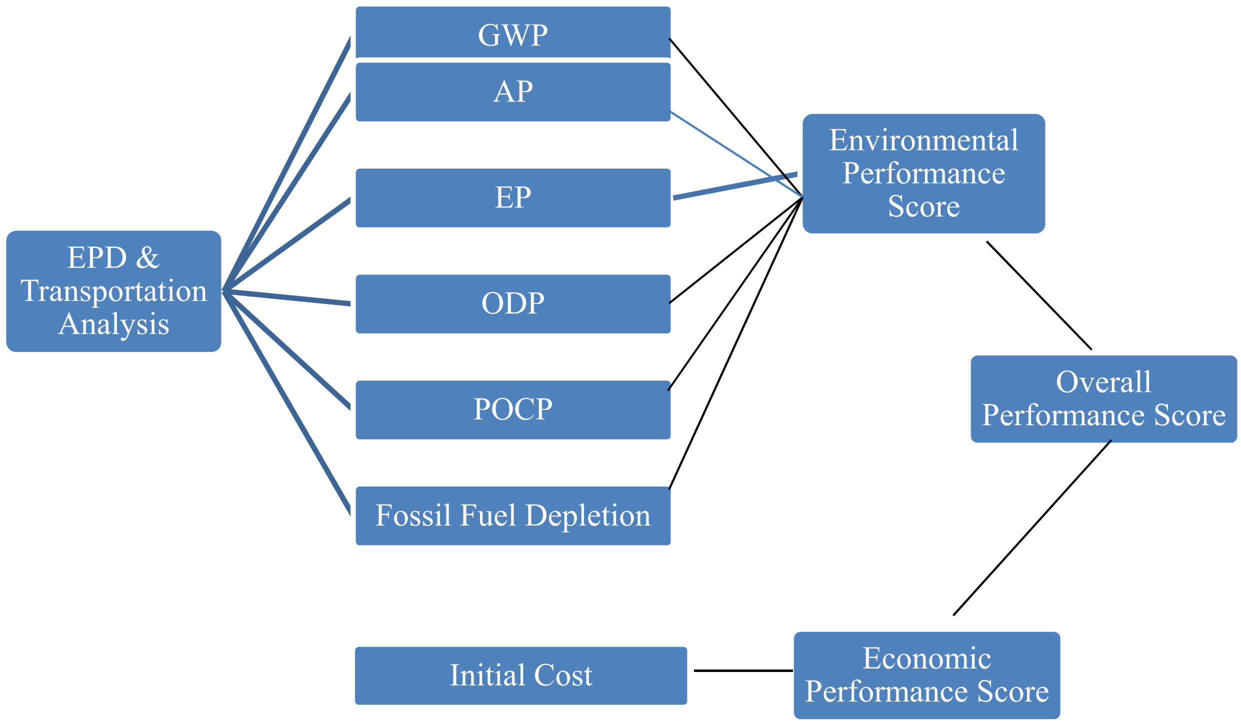


Figure 20
Computation of overall performance score

Sensitivity Analysis

Sensitivity analysis is a technique for estimating the effects of changing an independent variable on a dependent variable under a given set of methods and assumptions. Sensitivity checks verify the reliability of the sensitivity analysis results and provide a relevant approach for making conclusions and recommendations *[1]*. Sensitivity analysis plays a vital role in decision-making, as it determines the key variables that most influence the environmental performance of a pavement alternative. Most of the LCA study conducts a sensitivity analysis in order to identify the major influencing factor and to implement plans to reduce the adverse change due to these parameters.

Sensitivity analysis should be carried out in a systematic technique to determine the presence of significant differences, or to identify negligible LCI results. For a sensitivity analysis, identification of the sensitive variables that alter decision-making should be identified. In this regard, this section presents a sensitivity analysis conducted to determine how the change in the following inventory data would influence the overall environmental impacts of pavement design/product alternatives. The independent variables adopted for the sensitivity analysis were as follows:

- Environmental impacts of raw materials extraction and manufacturing, reported from EPD (A1);
- Environmental impacts associated to the production of pavement mixes (A3);
- Impacts of total distance travelled from raw material extraction to project location.

The sensitivity analysis was conducted by assuming an increase of 20% in the independent variables. The overall environmental performance together with the six impact categories (after the change in the independent variables) are presented in Tables 17 and 18 and are illustrated in Figure 21. The percentage increases in the overall environmental impacts, along with the six impact categories, are due to the changes in the aforementioned factors, presented in Table 17.

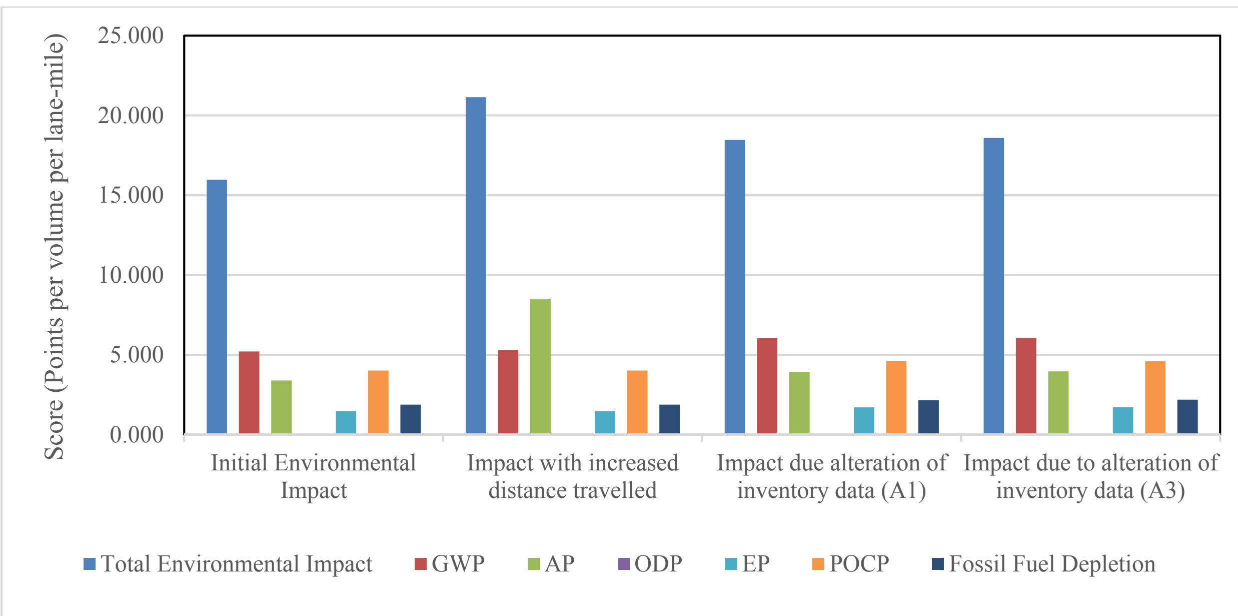


Figure 21
Environmental impact due to the change in inventory and primary variable

Table 17
Environmental impacts due to the change in inventory and primary variables

Inventory Metrics/Primary variable	Total	GWP	ODP	AP	EP	POCP	Fossil
Initial Environmental Impact	15.973	5.212	0.005	3.398	1.467	4.013	1.878
Impact with increased distance travelled	21.140	5.292	0.005	8.484	1.467	4.014	1.878
Impact due alteration of inventory data (A1)	18.461	6.046	0.006	3.933	1.707	4.605	2.163
Impact due to alteration of inventory data (A3)	18.581	6.076	0.006	3.966	1.733	4.614	2.186

Table 18
Increase in total environmental and impact categories

Inventory Metrics/Primary variable	Total	GWP	ODP	AP	EP	POCP	Fossil
Impact with increased distance travelled	32.35	1.54	0.000	149.64	0.0	0.02	0.000
Impact due alteration of inventory data (A1)	15.57	16.01	16.27	15.74	16.36	14.74	15.20

From Figure 21 and Table 18, it can be concluded that the overall environmental impacts are highly influenced by the hauling distance of concrete mixes from the plant location to the job site. The impact on environmental performance is similar, due to an alteration of inventory data for the A1 and A3 phases. A change in these criteria carries lesser impact than the transportation stage. For impact categories, acidification potential is significantly influenced by the change in distance travelled; whereas, the ozone depletion potential, eutrophication potential and fossil fuel depletion shows no major change. The global warming potential was the least affected by the changes due to the distance travelled and was equally influenced by the change in the inventory values of the A1 and A3 phases. All other impact categories, apart from the acidification potential, were least influenced by the transportation phase and were highly influenced by the change in inventory value associated with Phase 3. However, there was no large difference in change of percentile between A1 and A3. The results of the sensitivity analysis illustrated the importance of the transportation module, which was identified as the most influential factor in the quantification of environmental impacts.

Statistical Analysis

The decision-making tool quantifies the overall performance of multiple design and products. The lowest overall performance score represents the most sustainable design alternative. However, it is not certain whether the difference in overall performance score is significantly different or not. Therefore, a statistical analysis should be conducted to determine whether there were statistical significant differences between the overall performance values of multiple design alternatives considered in the analysis. An example of statistical analysis was conducted to estimate the statistical differences between multiple design alternatives. In this context, three different designs, each with four different mixes, were considered. The inventory data for each mix were extracted from the EPD database. Since the transportation impact for all designs were the same, the scope of the analysis was limited to the initial three phases of the considered system boundary. All the mixes considered in the analysis were Louisiana products. The details of the design and environmental impacts associated with the alternative designs and mixes are shown in Table 19.

Table 19
Description of the designs and environmental score of each mix

Design #	Mixes	Environmental Score (Points per yd^3 per lane-mile)
1 (6000 psi Compressive Strength & 13" Thick slab)	1	15.679
	2	15.668
	3	15.664
	4	15.658
2 (5000 psi Compressive Strength & 14" Thick slab)	5	16.529
	6	16.91
	7	17.292
	8	17.705
3 (7500 psi Compressive Strength & 12" Thick slab)	9	16.203
	10	26.785
	11	16.203
	12	19.893

The statistical analysis was conducted based on an analysis of variance (ANOVA) at a confidence level of 95%. For better representation and analysis, the results of the statistical analysis of the environmental impacts of each design is shown in Table 20, and the results of the ANOVA are shown in Table 21. The ANOVA table shows that the resulting P-value was 0.1823, which was greater than 0.05. Therefore, from these results, we can conclude that the overall environmental impacts associated with the different pavement design alternatives were not significantly different at a 95% confidence level.

Table 20
Descriptive statistical analysis of environmental performance of multiple design

Design	N	Sum	Mean	Corrected SS	Variance	Std Dev	Std Error
1	4	62.669	15.667	0.000235	0.000078	0.008846	0.004423
2	4	68.436	17.109	0.765	0.255	0.505	0.252
3	4	79.084	19.771	74.672	24.891	4.989	2.495
Total	12	210.189	17.516	110.111	10.010	3.164	0.913

Table 21
ANOVA results

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	34.674	17.337	2.07	0.1823
Error	9	75.437	8.382		
Corrected Total	11	110.111			

SOFTWARE DEMONSTRATION

Software Model

The developed methodology was incorporated into a Windows-based, decision-making software tool. This tool benchmarks and compares the considered pavement alternatives that meet the engineering performance criteria. The software evaluates the sustainability of the considered pavement alternatives using one of two modes of analysis: benchmarking and product comparison. The benchmarking mode of analysis provides the baseline results by averaging the impacts associated with all the selected pavement products. Product comparison, on the other hand, compares each individual mix separately and identifies the most sustainable product.

The software measures pavement sustainability in four different steps, with each step being addressed by one separate tab, i.e., layer information, weights, transportation, and summary/export. The software requires that the user input different parameters for the analysis. These parameters are the same for all analysis steps of both rigid and flexible pavements, except for the layer information tab. The design procedure and mix design of these two pavement types are different; therefore, the input parameters for one type differ from the other. Considering this factor, two different layer information user' interfaces were developed. The software evaluates the sustainability of only one layer for rigid pavements, whereas it can evaluate the performance of up to two layers for flexible pavements. Apart from these, the user interface and input for parameters are the same for the other steps. The four steps/tabs of the software are presented in the following sections.

Layer Information

This step defines the design/mixes that meet the pavement design criteria and user preferences. The user can input multiple design and multiple products to be evaluated. As mentioned earlier, this software has two modes of analysis: Benchmarking and Product Comparison. Regardless of the pavement type, the user needs to define the purpose of analysis at the start. If a user wants to assess the sustainability measure/baseline results for each considered design, benchmarking should be used, since benchmarking averages all the mixes selected for a design. Yet, if the user wants to find the most sustainable pavement mix/ product, the user should select the product comparison option. Product comparison measures and thereby declares the most cost-effective and environmentally preferred product. As shown in Figure 22, the software requires the input of the zip code of the proposed project in this step, which is used in the transportation analysis. The user interfaces for both pavement types are different and therefore are explained separately.

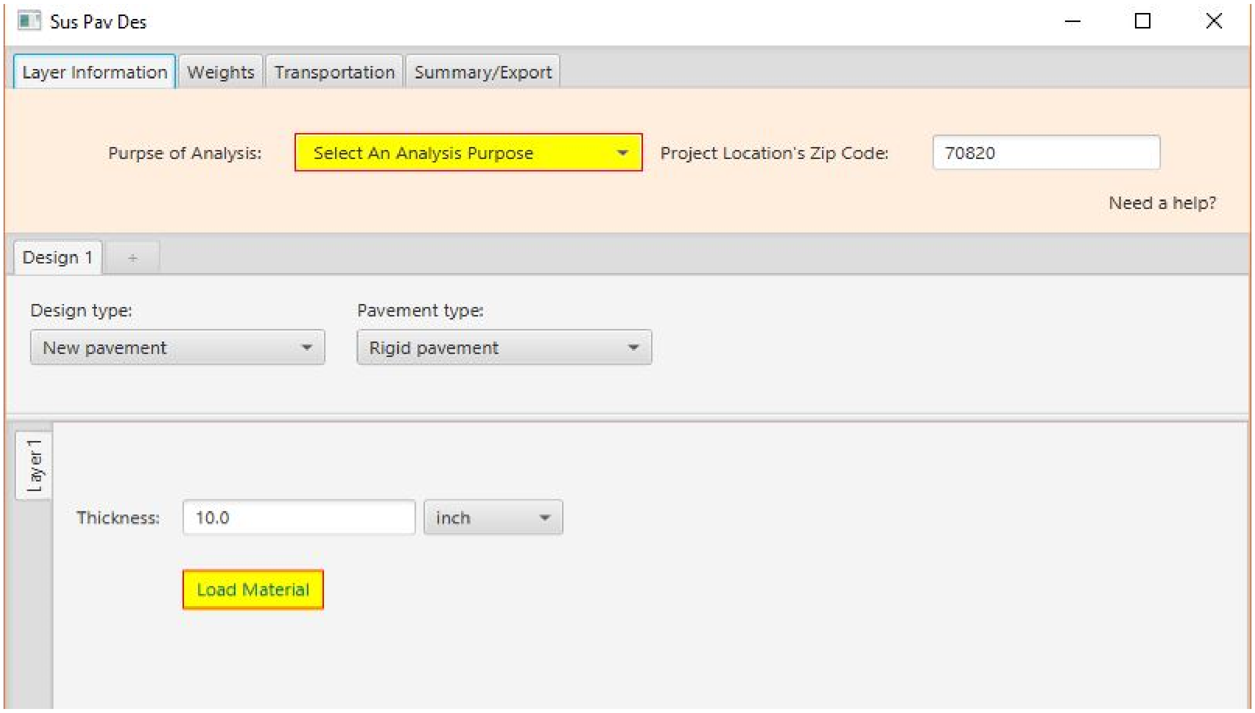


Figure 22
Layer information tab (rigid pavement)

Rigid Pavement. The software evaluates the sustainability of a single layer for rigid pavement. Therefore, the only input required for pavement design in the layer information tab is the thickness of the proposed pavement. As shown in Figure 23, the process is followed by selecting the mixes that meet the design criteria by clicking the load material tab within the layer information. This will open a new window, to select mix/mixes. A rigid pavement design is based on different parameters, i.e., modulus of elasticity, traffic load, subgrade modulus reaction, compressive strength, etc. However, this study considers only the compressive strength as a criterion for the selection of the mixes. The software filters the mixes as per the compressive strength value and region specified by the user. As illustrated in Figure 23, the mixes can be further filtered by specifying the raw materials content of the concrete mixes, i.e., cement content, fly ash content, and so on. Depending upon the mode of analysis, the software allows the user to select multiple mixes, one at a time.

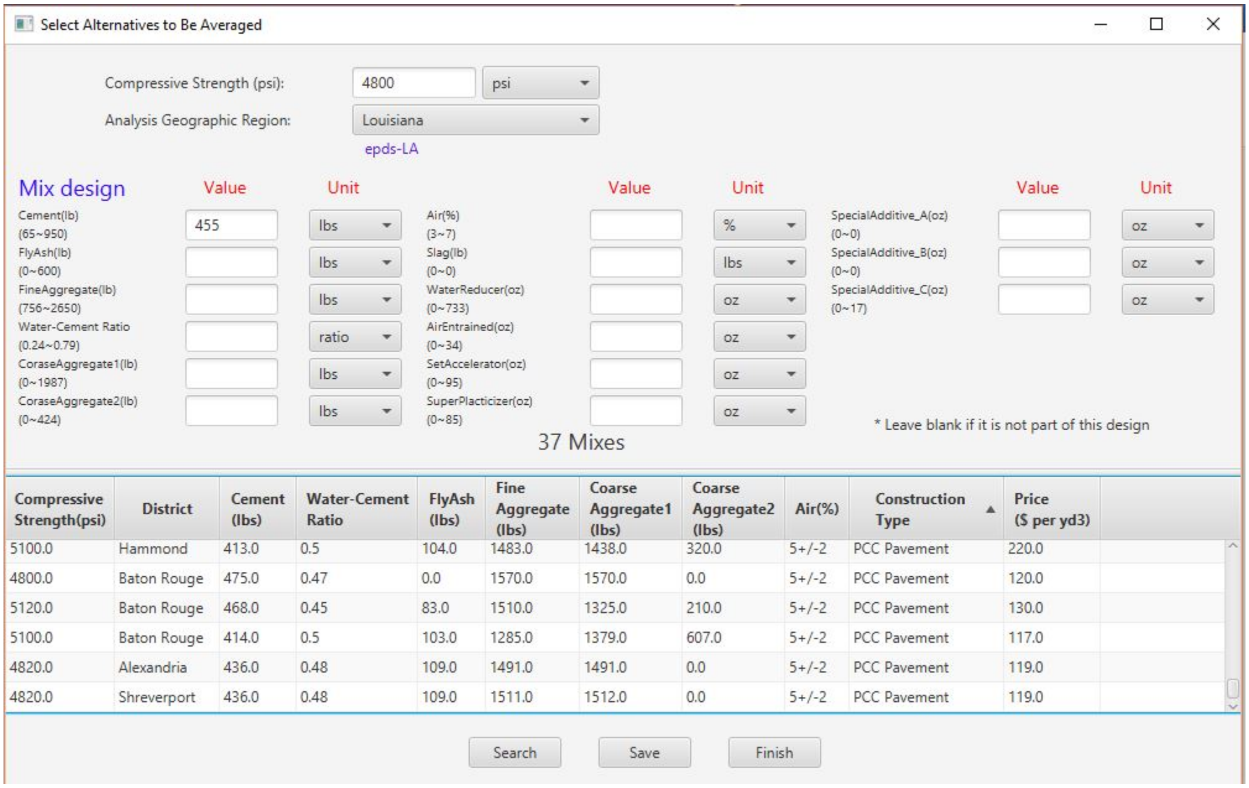


Figure 23
Rigid pavement mixes selection window

Flexible Pavement. Flexible pavement is a multi-layer system with asphalt layers at the top. Since the binder layer and wearing course uses a significant amount of asphalt, it is necessary to consider both layers to evaluate the sustainability of a flexible pavement. Therefore, both layers were considered in the developed tool; the user can decide to choose either a single layer or two asphalt-based layers. The user interface, illustrated in Figure 24, allows user to define multiple layer for the asphalt pavement analysis. For each layer, either binder or wearing, the user are allowed to select the appropriate flexible pavement design by selecting a mix type, together with the input of pavement thickness.

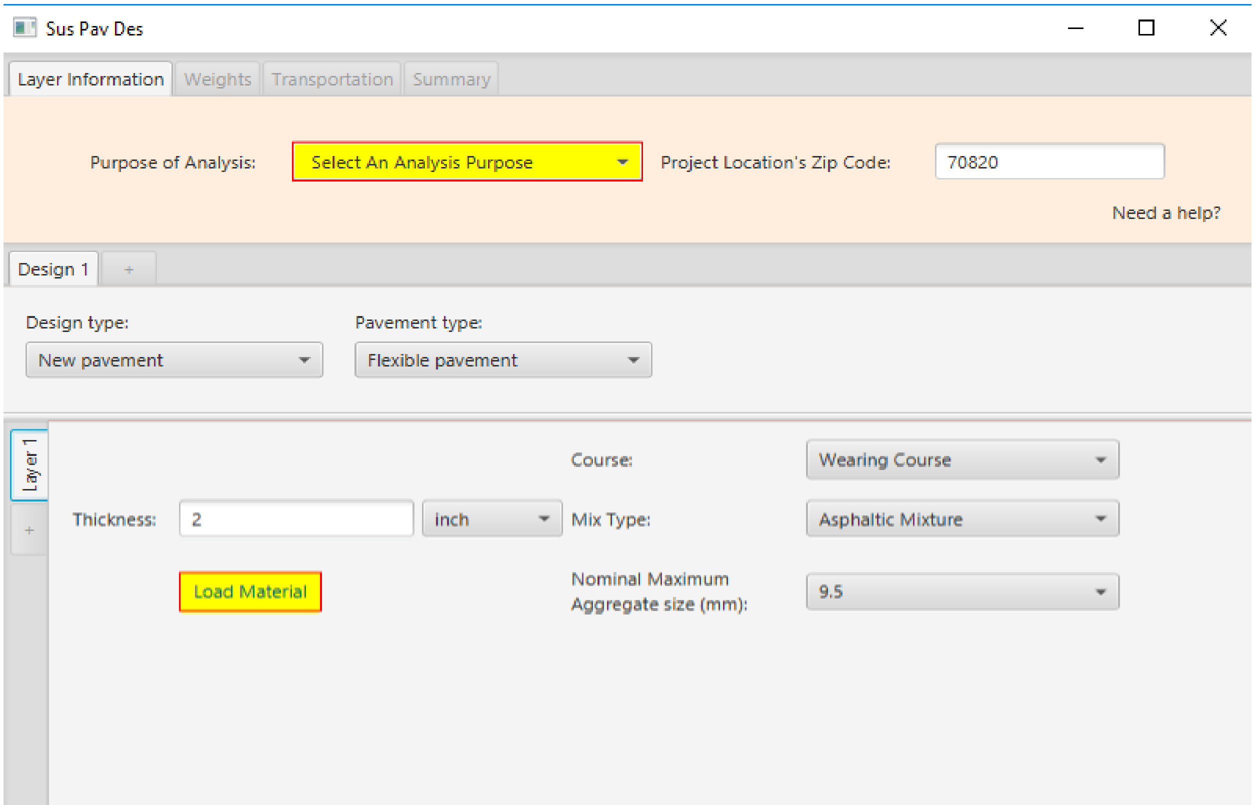


Figure 24
User interface for flexible pavement

As in rigid pavement, the process of defining pavement design is followed by selecting the proper mix that meets the design/engineering performance criteria. All the mixes used in the analysis were based on the Superpave mix design. Since flexible pavement has no single parameter that defines the performance of a mix design, the program filters the mixes based on the Superpave volumetric mix design as defined by the user. The mix selection window, presented in Figure 25, allows the user to input parameters such as binder grade, content, RAP content, aggregate content, etc., and the software provides the most suitable mix within a certain tolerance.

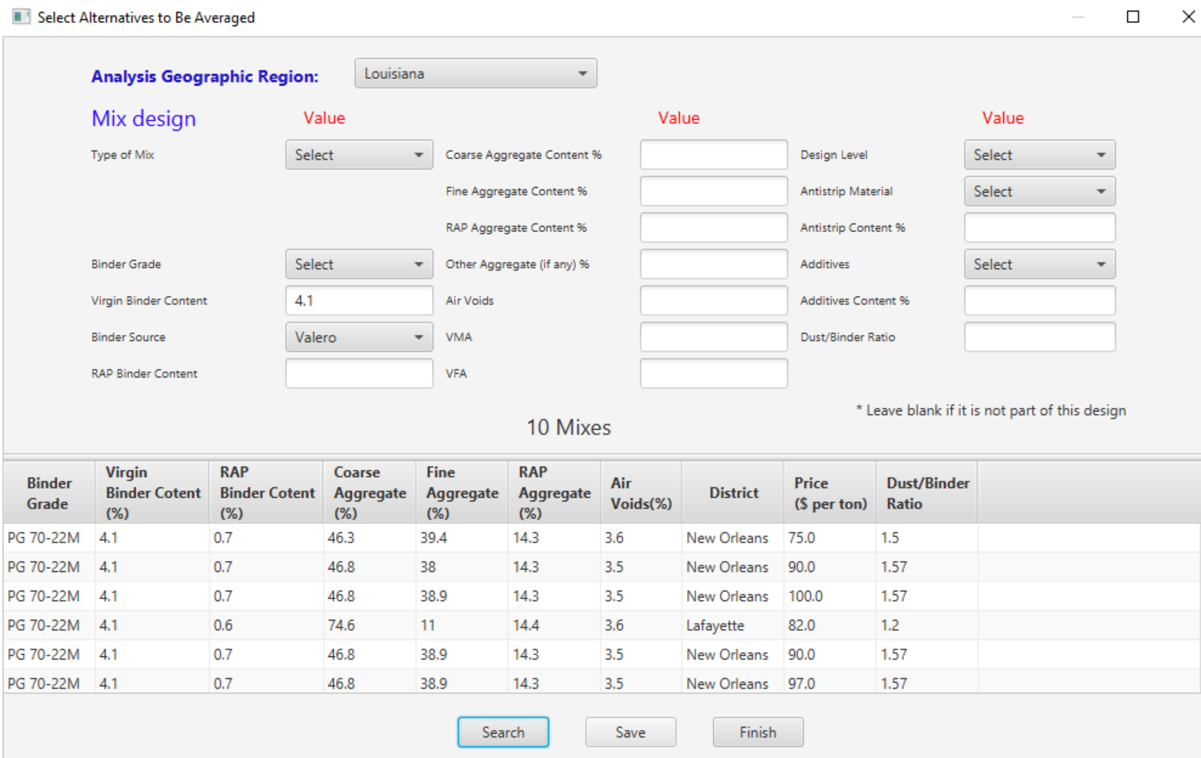


Figure 25
Flexible pavement mix selection window

Weights

The analysis requires user input for weights of economic and environmental performance criteria. The default weights assigned for each performance criterion, shown in Figure 26, is 50%; however, the user can modify the values as per individual preference. The weights in relation to the environmental impact categories may be selected from four different sets. A user-defined set of weights allows the user to define weights based on individual preferences and value choices.

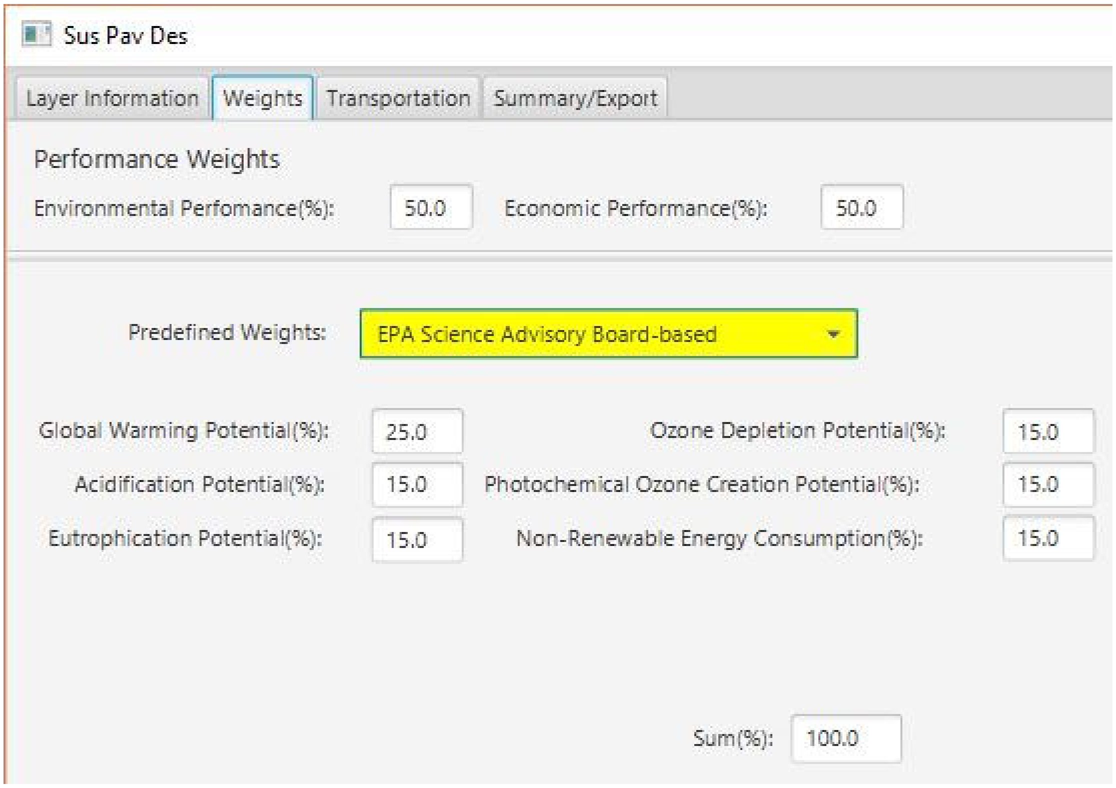


Figure 26
Software performance weights tab

Transportation

The third step in the computation of transportation analysis is drawn from the last phase of environmental analysis. As illustrated in Figure 27, the primary data required for the evaluation of transportation impact is vehicular characteristics, fuel type, and distance traveled. The user can select the respective vehicle and fuel type from the different categories defined in the program. Based on the defined characteristics, the program extracts the corresponding inventory data for the analysis. For distance traveled, the program can calculate using two different methods. The first method requires the zip code input of respective plant locations; the internet calculates the distance between the project site and the plant location. The project zip code is entered at the very onset of the program, in the layer information tab. If internet is not available or if the zip code of either plant or job site is unknown, the user can enter the distance manually in miles. The adopted equation, previously defined in the report, is used for impact analysis due to the transportation.

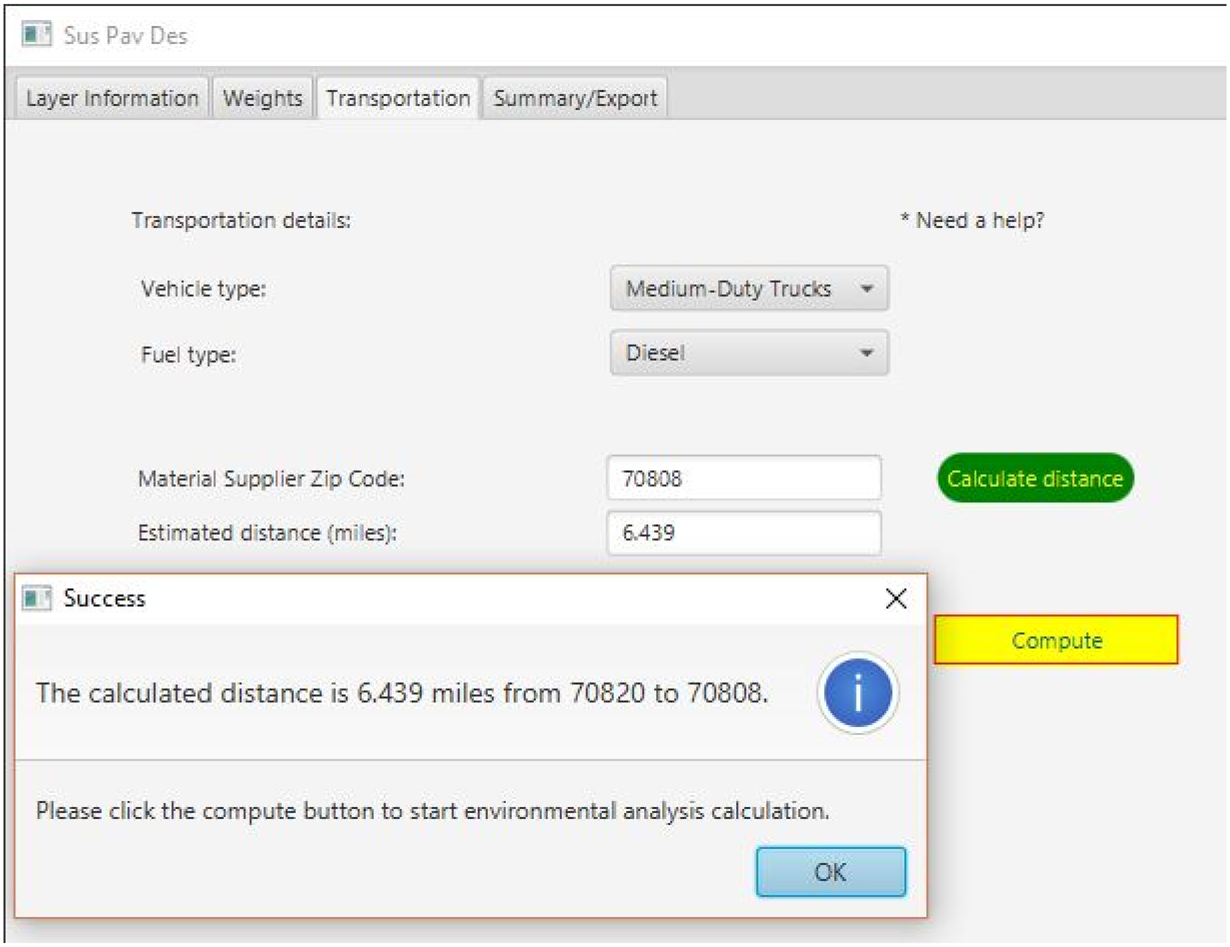


Figure 27
Transportation impact analysis tab

Summary/Export

The results of the analysis may be viewed in the Summary/Export tab of the software. The software allows the user to view and export the analysis report, either for each design separately or for all the considered design alternatives. Since for asphalt pavement multiple layers are selected, this tab allows the user to view the output either for a single layer or for all layers. Further, the analysis report presents the performance either in a summary graph or a life-cycle stage graph. The summary graph, as illustrated in Figure 28, shows the overall performance, economic performance, and environmental performance of all designs or a single design. In addition to the summary graph for environmental performance, the software presents the impacts in a life-cycle stage graph. This graph shows the impact of each phase separately, i.e., A1, A2, and A3, for total environmental performance and for each impact category. Since ISO 14045 recommends representation of a normalized value along with the weighted value, the software has a user option to view either non-weighted or weighted impact values. In the context of economic performance, the software shows both the initial and material costs for Louisiana products. For other regions, the software displays only material costs. As mentioned in the previous sections of this report, this study has no EPD for asphalt materials, and hence the software cannot measure the flexible pavement environmental performance. Yet, based on the developed framework, and after the addition of the asphalt EPDs in the database, the program will be executable to measure the sustainability of flexible pavements as in rigid pavements. For the economic performance of asphalt products, due to unavailability of the material cost, only initial cost was considered; and may be viewed in the summary/export tab.

For each combination of selection, the results can be exported into the excel file via table export option. The exported excel file provides details of all the mixes/design considered in the analysis along with the performance score for corresponding selection i.e. overall, environmental or economical.

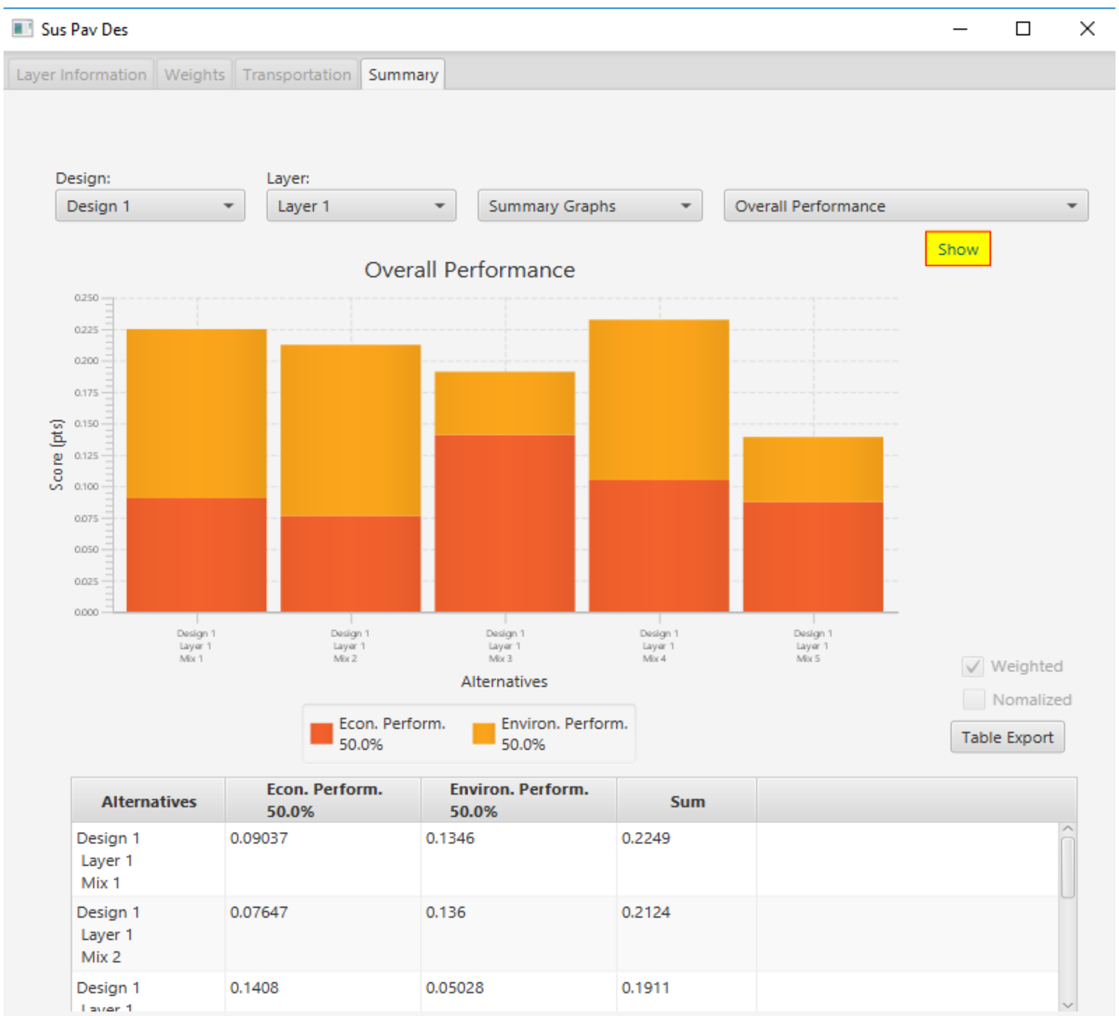


Figure 28
Output of the program for overall performance

CONCLUSIONS

Over the years, different agencies and stakeholders implemented sustainable technologies in pavement applications; these technologies tend to reduce negative environmental impacts. Even though environmental impacts have been a primary concern to multiple agencies, only a few are willing to pay for the reduction of such impacts. Therefore, sustainable pavement technologies that tend to reduce cost and negative environmental impacts concurrently are sought. A literature review of past studies showed that life-cycle assessment has been considered as the primary pavement sustainability measurement tool. However, due to a lack of standard practices to conduct LCA, different studies used different system boundaries and data sources. These inconsistent practices, combined with the consideration of environmental performance, limits the use of LCA. Therefore, to date, an effective sustainable measuring tool is lacking to balance the economic and environmental performances of pavements.

The objective of this study was to conceive and develop a sustainability measurement tool that may be integrated into routine pavement design. The main purpose of such a tool is to aid in decision-making by providing a comparison of different pavement designs/products with respect to the environment and economic functionalities. The methodology may also be used to provide baseline results of the environmental impacts. EPD, as a consistent and comparable sustainability measurement tool, has been adopted in this study for the environmental analysis. EPD quantifies the environmental impacts from raw material extraction to the transportation of the pavement mixes to the job site, a cradle-to-gate framework. To achieve this objective, EPDs were collected from different sources and were classified into different regions: nation-wide, south-central region, and statewide region (Louisiana). For economic performance, the system boundary is similar to the environmental analysis. The initial cost and the material cost were used to evaluate the economic performance of industry-wide, average EPD products, and individual EPD product, respectively. The main difference between material cost and initial cost is that the latter accounts for the costs such as the material transport from plant to job site, labor, equipment, and overhead.

A window-based software was developed, based on the developed framework. The software database is editable and expandable, so that the user can add more EPD products as they become available. Since EPD is highly dependent upon the location, the software database is editable and expandable, such that the users can add more products to the database as needed. The software also allows the user to define different parameters, such as pavement design, mixes, vehicular characteristics, performance weights, and environmental impact category weights. There is no standard consensus for performance and environmental impact category weights; therefore, the program allows the user to input these values according to individual experience in tandem with the relative importance of impact categories. The user can view the output in tabular and graphical form for both the weighted and non-weighted performance. The user can also view the results of the total environmental performance, a life-cycle stage graph for environmental impacts, economic performance, and combined overall performance. The program also exports all the results along with the mix design details into the excel sheet. The intended audience for the developed software would be manufacturers, designers, and consumers. These individuals would use the software to benchmark their products and to select cost-effective and environmental-friendly solutions. Selecting a product that has an optimum balance between economic and environmental components presents a compelling, innovative way to achieve sustainability in pavement applications.

RECOMMENDATIONS

The main challenge faced in the study was associated with the availability of data. In the context of rigid pavement, many issues were associated with proprietary issues related to the EPD and mix design, especially for the state of Louisiana. For the EPD data collection, the proprietary issues were associated with different companies, and coupled with a limited knowledge on pavement sustainability. This limitation resulted in issuing an industry-average EPD, rather than relying on individual company EPD. With respect to asphalt pavement, EPDs were not available for asphalt materials. Therefore, the study only developed the framework for the analysis of flexible pavements.

The developed framework is suitable to compare design alternatives based on a cradle-to-gate framework. Yet, other pavement phases carry significant impacts on all three components of sustainability. A lack of proper quantification exists for the impact from the use phase and the end-of-life phase. Therefore, for future consideration, the study may be expanded to quantify the sustainability of the product by considering the other phases of the pavement life cycle as well. A sustainability developed by considering all phases of pavement life cycle along with quantification of social components would allow for a more accurate assessment of pavement sustainability.

The developed tool cannot be used for the comparison of flexible and rigid pavements. Therefore, a systematic approach is needed for comparison between different types of pavement. In addition, developing and using a consistent EPD protocol would result in a more accurate comparison of pavement alternatives. It is also noted that this study only collected EPD for plain concrete. Since continuously reinforced pavement is also used in pavement applications, it is recommended to develop EPDs for reinforced concrete as well.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AC	Asphalt Concrete
AP	Acidification Potential
BEES	Building for Environmental and Economic Sustainability
CH4	Methane
CO	Carbon Monoxide
CO2	Carbon Dioxide
CO2eq	Carbon Dioxide Equivalent
CY	Cubic Yard
DOT	Department of Transportation
DOTD	Louisiana Department of Transportation and Development
EIO	Economic Input Output
EIO-LCA	Economic Input-Output Life-Cycle Assessment
EOL	End-of-Life
EP	Eutrophication Potential
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
FHWA	Federal Highway Administration
GHG	Greenhouse Gas
GWP	Global Warming Potential
HMA	Hot-Mix Asphalt
ISO	International Organization for Standardization
LCA	Life-Cycle Assessment
LCCA	Life-Cycle Cost Analysis
LCI	Life-Cycle Inventory
LCIA	Life-Cycle Impact Assessment
M&R	Maintenance and Rehabilitation
MEPDG	Mechanistic-Empirical Pavement Design Guide
NRMCA	National Ready-Mix Concrete Association
N_2O	Nitrous Oxide
NO_x	Nitrogen Oxides
ODP	Ozone Depletion Potential
PaLATE	The Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
PCA	Portland Cement Association
PCR	Product Category Rule

PE2	Project Emission Estimator
POCP	Photochemical Ozone Creation Potential
RAP	Recycled Asphalt Pavement
SCM	Supplementary Cementitious Material
SO_2	Sulfur Dioxide
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
VOCs	Volatile Organic Compounds

REFERENCES

1. Harvey, J. T.; Meijer, J.; Ozer, H.; Al-Qadi, I. L.; Saboori, A.; and Kendall, A. *Pavement Life-Cycle Assessment Framework*. Report FHWA-HIF-16-014. FHWA, U.S. Department of Transportation, July 2016.
2. Environmental Protection Agency (EPA). *Inventory of U.S. Greenhouse Gas Emissions and Sinks:1990–2009*. Report EPA 430-R-13-001, Environmental Protection Agency, 2012.
3. Hassan, M. "Life-cycle Assessment of Titanium Dioxide Coatings." In *Construction Research Congress 2009: Building a Sustainable Future*, 2009, pp. 836-845.
4. Van Dam, T. J.; Harvey, J. T.; Muench, S. T.; Smith, K. D.; Snyder, M. B.; Al-Qadi, I. L.; and Kendall, A. *Towards Sustainable Pavement Systems: A reference document.* Report FHWA-HIF-15-002, FHWA, U.S. Department of Transportation, January 2015.
5. Mukherjee, A. "Life-Cycle Assessment of Asphalt Mixtures in Support of an Environmental Product Declaration." National Asphalt Pavement Institution, Lanham, Maryland, June 2016.
6. Del Borghi, A.; Strazza, C.; Gallo, M.; Messineo, S.; & Naso, M. "Water Supply and Sustainability: Life Cycle Assessment of Water Collection, Treatment, and Distribution Service." *The International Journal of Life Cycle Assessment,* Vol. 18, No. 5, June 2013, pp 1158-1168.
7. Mukherjee, A.; and Dylla, H. "Challenges to Using Environmental Product Declarations in Communicating LCA Outcomes: The Case of the Asphalt Industry." *In Transportation Research Record 2639.* Transportation Research Board, National Research Council, Washington D.C., 2017, pp 84-92.
8. AzariJafari, H.; Yahia, A.; and Amor, M. B. "Life-cycle Assessment of Pavements: Reviewing Research Challenges and Opportunities." *Journal of Cleaner Production*, Vol. 112, January 2016, pp 2187-2197.
9. Federal Highway Administration (FHWA) and U.S. Department of Transportation *Environmental Review Toolkit.* www.environment.fhwa.dot.gov/strmlng/index.asp, Accessed on December 15, 2017
10. Lamptey, G.; Ahmad, M. Z.; Labi, S.; and Sinha, K. C. "Life-cycle cost analysis for INDOT pavement design procedures." Report FHWA/IN/JTRP-2004/28, Indiana Department of Transportation, March 2005.

11. Ozbay, K.; Jawad, D.; Parker, N.; and Hussain, S. "Life-cycle Cost Analysis: State of the Practice versus State of the Art." *Transportation Research Record 1864.* Transportation Research Board, Washington D.C., 2005, pp.62-70.

12. U.S. Department of Transportation, *Life-Cycle Cost Analysis Primer*, Report FHWA IF-02-047, Office of Assets Management, U.S. Department of Transportation, Federal Highway Administration, August 2002. https://www.fhwa.dot.gov/asset/lcca/010621.pdf.

13. Walls III, J. and Smith, M.R., *Life-cycle Cost Analysis in Pavement Design* FHWA-SA-98-079, FHWA, U.S. Department of Transportation, September 1998.

14. Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Norris, G.; Rydberg, T.; Schmidt, W.P.; Suh, S.; Weidema, B.P.; and Pennington, D.W. "Life Cycle Assessment: Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications." *Environment international*, Vol 30, No 5, 2004, pp.701-720., July 2004

15. Santos, J.; Flintsch, G.; and Ferreira, A. "Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability." *Resources, Conservation and Recycling,* Vol 116, January 2017, pp. 15–31.

16. Anderson, D.I.; Peterson, D.; Sheppard, L.W.; Sy, C.C. *Pavement Design and Rehabilitation Strategies*. Project FHWA/UT-79-6, Utah DOT, Government Publications Clearinghouse, Springfield, VA, 1979.

17. Evans, M. "Using Life Cycle Cost Analysis in Highway Project Development." Preliminary Investigation, Caltrans Division of Research and Innovation, 2011.

18. Wang, T.; Lee, I.S.; Kendall, A.; Harvey, J. Lee, E.B. and Kim, C. "Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance." *Journal of Cleaner Production*, 33, 2012, pp.86-96.

19. International Organization for Standardization (ISO) 14044. "Environmental Management – Life-Cycle Assessment Requirements and Guidelines (ISO 2006b)." International Organization for Standardization, Geneva, Switzerland, 2006.

20. Mukherjee, A., and Cass, D. "Project emissions estimator: implementation of a project-based framework for monitoring the greenhouse gas emissions of pavement." In *Transportation Research Record 2282.* Transportation Research Board, National Research Council, Washington D.C., 2012, pp. 91-99.

21. Weiland, C.D. and Muench, S.T. "Life cycle assessment of Portland cement concrete interstate highway rehabilitation and replacement." No. WA-RD 744.4, Washington State. Dept. of Transportation. Office of Research and Library Services, Washington, Feburary 2010.

22. Spielmann, M.; and Scholz, R. "Life cycle inventories of transport services: Background data for freight transport (10 pp)." *The International Journal of Life Cycle Assessment*, Vol 10 No. 1, January 2005, pp. 85-94.

23. Mroueh, U.; Eskola, P.; Laine-Ylijoki, J.; Wellman, K.; Juvankoski, E.M.M.; Ruotoistenm€aki, A. "Life Cycle Assessment of Road Construction. Highlights of Finnra Reports 2000." Finnish National Road Administration, Helsinki, Finland, 2000.

24. Loijos, A. A. N. "Life cycle assessment of concrete pavements: impacts and opportunities." Master theses, Massachusetts Institute of Technology, Massachusetts, May 2011.

25. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R., Hellweg, S.; Koehler, A.; Pennington, D. and Suh, S. "Recent developments in life cycle assessment." *Journal of environmental management*, Vol 91, No. 1, October 2009, pp.1-21.

26. Pennington, D.W.; Potting, J.; Finnveden, G.; Lindeijer, E.; Jolliet, O.; Rydberg, T. and Rebitzer, G. "Life cycle assessment Part 2: Current impact assessment practice." *Environment international*, Vol. 30, No. 5, July 2004, pp.721-739.

27. Lave, L.B. "Using input– output analysis to estimate economy wide discharges." *Environmental Science & Technology*. Vol 29, No. 9, September 1995, pp. 420–426.

28. Lenzen, M. "Errors in conventional and input–output-based life-cycle inventories." *Journal of Industrial Ecology.* Vol 4, October 2000, pp. 127–148.

29. Inyim, P.; Pereyra, J.; Bienvenu, M.; and Mostafavi, A. "Environmental assessment of pavement infrastructure: A systematic review." *Journal of Environmental Management*, Vol 176, July 2016, pp. 128–138.

30. Akbarian, M., Moeini-Ardakani, S., Ulm, F. J., & Nazzal, M. "Mechanistic approach to pavement-vehicle interaction and its impact on life-cycle assessment." In *Transportation Research Record 2306*, Transportation Research Board, Washington D.C, 2012, pp. 171-179.

31. Taylor, G. W.; Marsh, P.; and Oxelgren, E. "Effect of Pavement Surface Type on Fuel Consumption-Phase II: Seasonal Tests." Report No. CSTT–HWV–CTR–041, Portland Cement Association, Skokie, Illinois, 2000.

32. Berthiaume, R.; and C Bouchard. "Exergy analysis of the environmental impact of paving material manufacture." *Transactions of the Canadian Society for Mechanical Engineering*, Vol 23, No. 1B,1999, pp. 187-196.

33. Nathman, R. K. "PaLATE user guide, example exercise, and contextual discussion." Master theses, University of Delaware, Delaware, May 2008.

34. Liu, X.; Cui, Q.; and Schwartz, C. "Greenhouse gas emissions of alternative pavement designs: Framework development and illustrative application." *Journal of environmental management*, Vol. 132, January 2014, pp. 313-322.

35. Chan, A. W. C. "Economic and Environmental Evaluations of Life-Cycle Cost Analysis Practice: A Case Study of Michigan DOT Pavement Projects" Doctoral dissertation, University of Michigan, Michigan, March 2007.

36. Carpenter, A. C.; Gardner, K. H., Fopiano, J.; Benson, C. H.; and Edil, T. B. "Life cycle based risk assessment of recycled materials in roadway construction." *Waste Management,* Vol. 27, No. 10, January 2007, pp. 1458-1464.

37. Birgisdóttir, H., and Christensen, T. H. "Life cycle assessment model for road construction and use of residues from waste incineration" Doctoral dissertation, Technical University of Denmark, Denmark, July 2005.

38. Birgisdottir, H.; Christensen, T. H.; Bhander, R.; and Hauschild, M. Z. "LCA-tool for disposal of MSWI residues: Recycling in road construction and landfilling." In *10th International Waste Management and Landfill Symposium*. CISA, Environmental Sanitary Engineering Centre, 2005.

39. Haapio, A. and Viitaniemi, P. "A critical review of building environmental assessment tools." *Environmental impact assessment review,* Vol. 28, No. 7, October 2008, pp. 469-482.

40. Santos, J.M.; Thyagarajan, S.; Keijzer, E.; Flores, R.F; and Flintsch, G. Pavement life cycle assessment-a comparison of American and European tools. In *Pavement Life-Cycle Assessment Symposium 2017*. Transportation Research Board, National Research Council, Washington D.C., April 2017.

41. Lipiatt, B. C. "BEES 4.0–building for economic and environmental sustainability (technical manual and user guide)." National Institute for Standards and Technology, August 2007.

42. International Organization for Standardization. “Environmental labels and declarations—self-declared environmental claims (type II environmental labelling).” European Standard EN ISO 14021. International Organization for Standardization, 1999.

43. International Organization for Standarization. “Environmental labels and declarations—type I environmental labelling—principles and procedures.” European Standard EN ISO 14024. International Organization for Standardization, 1999.

44. United Nations Officer for Project Services. “A guide to environmental labels for procurement practitioners of the United Nations system.” United Nations Officer for Project Services, Denmark, 2009.

45. International Organization for Standardization. “Environmental labels and declarations—type III environmental declarations—principles and procedures.” European Standard EN ISO 14025. International Organization for Standardization, 2006.

46. Schmincke, E.; and Grahl, B. “The part of LCA in ISO type III environmental declarations.” *International Journal of Life Cycle Assessment*, Vol 12, August 2007, pp. 38-45.

47. U.S. Department of Transportation, Federal Highway Administration. *Environmental Product Declarations and Product Category Rules.* https://www.fhwa.dot.gov/pavement/sustainability/articles/environmental.cfm. Accessed on December 06, 2017.

48. National Ready-Mix Concrete Association, 2014a. *NRMCA member industry-wide EPD for ready mixed concrete.* http://www.nrmca.org/sustainability/EPDProgram/Downloads/NRMCA%20EPD%20 10.08.2014.pdf. Accessed on December 06, 2017.

49. National Asphalt Pavement Association (NAPA). “Product Category Rules for Asphalt Mixtures (Version 1.0).” January 2104.

50. Del Borghi, A. "LCA and communication: environmental product declaration." *The International Journal of Life Cycle Assessment,* Vol. 18, Issue. 2, February 2013, pp. 293-295.

51. Amekudzi, A.; and M. Meyer. “Consideration of Environmental Factors in Transportation Systems Planning.” NCHRP Report 541, Transportation Research Board of the National Academies, Washington, D.C. 2005.

52. Wichelman, A.F. "Administrative agency implementation of the National Environmental Policy Act of 1969: A conceptual framework for explaining differential response." *Natural resources journal*, Vol. *16, No.* 2, April 1976, pp.263-300.

53. Oregon Department of Transportation. *Transportation Planning Rule. Transportation and Growth Management Policies & Plans,* Oregon Department of Transportation's Transportation Development Division (Planning); FHWA; May 2008.

54. Washington Department of Commerce, *Washington State Department of Commerce Growth Management*. www.cted.wa.gov/site/377/default.aspx. Accessed December 11, 2017.

55. Environment News Service. *Maryland Enacts Ambitious Climate Protection Law. May 12, 2009*. www.ens-newswire.com/ens/may2009/2009-05-12-092.asp. Accessed December 12, 2017.

56. Barrella, E.; Amekudzi, A.; Meyer, M.; Ross, C.; and Turchetta, D. "Best practices and common approaches for considering sustainability at US state transportation agencies." In *Transportation Research Record 2174,* Transportation Research Board, National Research Council, Washington DC, 2010, pp. 10-18.

57. Gorham, R. "Air Pollution from Ground Transportation: An assessment of causes, strategies and tactics and proposed sections for the international community." Division for Sustainable Development, Department of Economic and social affairs, United Nations, 2002.

58. U.S. Life Cycle Inventory Database. *National Renewable Energy Laboratory, 2012* https://www.lcacommons.gov/nrel/search, Accessed on June 10, 2017.

59. Bare, J. "Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI)." US Environmental Protection Agency, Ohio, July 2012.

60. Ryberg, M.; Vieira, M.D.; Zgola, M.; Bare, J; and Rosenbaum, R.K. "Updated US and Canadian normalization factors for TRACI 2.1." *Clean Technologies and Environmental Policy*, Vol. 16, No. 2, February 2014, pp.329-339.

61. Bureau of Labor Statistics., United States Department of Labor, 2017. https://www.bls.gov/cpi/. Accessed June 13, 2017.

62. Zavadskas, E.K.; Liias, R.; and Turskis, Z. "Multi-Attribute Decision-Making Methods for Assessment of Quality in Bridges and Road Construction: State-of-The-

Art Surveys." *Baltic Journal of Road & Bridge Engineering*, Vol. *3, No.* 3, September 2008, pp. 152-160.

63. Uzarowski, L. "Sustainable pavements— making the case for longer design lives for flexible pavements." Annual Conf. of the Transportation Association of Canada, Ottawa, Ontario, Canada. 2008.

64. Cooper, S. B.; Elseifi, M.; Mohammad, L. N.; and Hassan, M. "Performance and Cost-Effectiveness of Sustainable Technologies in Flexible Pavements Using the Mechanistic-Empirical Pavement Design Guide." *Journal of Materials in Civil Engineering*, Vol 24, No. 2, 2012, pp. 239–247.

65. Huang, Y. H. *Pavement analysis and design (2nd Ed)*. Pearson Prentice Hall. Institute and State University, 2004.

66. Babashamsi, P.; Md Yusoff, N. I.; Ceylan, H.; Md Nor, N. G.; and Salarzadeh Jenatabadi, H. "Sustainable Development Factors in Pavement Life-Cycle: Highway/Airport Review." *Sustainability, Vol.* 8, No. 3, March 2016.

67. Coree, B.; Ceylan, H; and Harrington, D. "Implementing the mechanistic-empirical pavement design guide: implementation plan." Iowa State University, Iowa, May 2005.

68. Buss, A.; Rashwan, M.; Breakah, T.; Williams, R. C.; and Kvasnak, A. "Investigation of warm-mix asphalt using the mechanistic empirical pavement design guide." Mid-Continent Transportation Research Symposium, Iowa State University, Iowa, 2009.

69. Goh, S. W.; Zhanping, Y.; and Van Dam, T. J. "Laboratory evaluation and pavement design for warm mix asphalt." Mid-Continent Transportation Research Symposium, Iowa State University, 2007.

70. Hu, J., Wang, K., and Ge, Z. "Study of the Mechanical Properties of Iowa Concrete Pavement for Use in the Mechanistic-Empirical Pavement Design Guide (MEPDG)." *Paving Materials and Pavement Analysis*, 2010, pp. 169–175.

71. Baus, R. L.; and Stires, N. R. "Mechanistic-Empirical Pavement Design Guide Implementation." FHWA-SC-10-01, The South Carolina Department of Transportation and The Federal Highway Administration, June 2010.

72. Damodaram, C.; Giacomoni, M.H.; Prakash Khedun, C.; Holmes, H.; Ryan, A.; Saour, W.; and Zechman, E.M. "Simulation of combined best management practices and low impact development for sustainable stormwater management." *JAWRA Journal of the American Water Resources Association*, Vol. 46, N0. 5, October 2010, pp.907-918.

73. Smith, R.; Freeman, T.; and Pendleton, O. “Pavement Maintenance Effectiveness.” Strategic Highway Research Program, National Research Council, Washington D.C, November 1993.

74. Prashant V. R.; John T. H.; Stephen T. M.; Imad L. Al.; Gerardo W. F.; Joep M.; Hasan O. *Sustainable Pavements Program Road Map Draft Document. Report* FHWA-HIF-17-029, FHWA, U.S. Department of Transportation, 2017.

75. Robinette, C., and Jon, E. "Energy, emissions, material conservation, and prices associated with construction, rehabilitation, and material alternatives for flexible pavement." In *Transportation Research Record* 2179. Transportation Research Board, National Research Council, Washington, D.C., 2010, pp. 10-22.

76. Energy Information Administration, States Energy Data System. *Asphalt and Road Oil and Other Petroleum Products. Consumption, Price and Expenditure Estimates.* https://www.eia.gov/state/seds/sep_fuel/html/fuel_ar.html, Accessed on November 2017.

77. FHWA, U.S. Department of Transportation. *Cold In-Place Recycling,* May 18, 2008.

http://www.fhwa.dot.gov/pavement/recycling/cir/map.cfm., Accessed on November 2017.

78. FHWA, U.S. Department of Transportation. *Recycled Asphalt Pavement— User Guideline.* May 27, 2008. http://www.tfhrc.gov/hnr20/recycle/waste/rap132.htm. Accessed in June 13, 2017.

79. Muench, S. T.; and Anderson, J. L. “Greenroads: a sustainability performance metric for roadway design and construction.” Report TNW2009-13, Transportation Northwest Regional Center X (TransNow), Washington, December 2009.

80. Muench, S. T.; Anderson, J.; and Bevan, T. “Greenroads: A sustainability rating system for roadways.” *International Journal of Pavement Research and Technology*, Vol 3, No. 5, September 2010, pp. 270-279.

81. Soderlund, M.; Muench, S. T.; Willoughby, K.; Uhlmeyer, J.; and Weston, J. “Green Roads: A sustainability rating system for roadways.” Proc., 87 TRB Annual Meeting, Washington DC, 2008.

82. Ramani, T.; Potter, J.; DeFlorio, J.; Zietsman, J.; and Reeder, V. “A Guidebook for Sustainability Performance Measurement for Transportation Agencies.” In Transportation Research Board 91st Annual Meeting, Report No. 12-3672, Washington D.C., 2012.

83. Simpson, S.P.; Ozbek, M.E.; Clevenger, C.M; and Atadero, R.A. “A framework for assessing transportation sustainability rating systems for implementation in US State Departments of Transportation.” Master Theses, Colorado State University, Colorado, December 2013.

84. Athalia, A. “Sustainable Streets and Highways: An Analysis of Green Roads Rating Systems Sustainable Streets and Highways.” Master Thesis, Georgia Institute of Technology, Georgia, May 2012.

85. Reid, L., Bevan, T.; Davis, A.; Neuman, T.; Penney, K., Seskin, S.; and Weiland, C. “Invest: Sustainable Highways Self-Evaluation Tool.” Federal Highway Administration, Washington, DC, 2015.

86. Washington State Department of Transportation. “WSDOT INVEST Pilot Study.” Washington State Department of Transportation and Federal Highway Administration, 2014.

87. Arizona Department of Transportation. “The Collaborative Benefits of Using FHWA’s INVEST – Arizona Department of Transportation Sustainability Implementation.” Federal Highway Administration, 2015 from https://www.sustainablehighways.org/779/72/arizona-dot-using-invest-to-integrate-sustainability.html.

88. Lee, J.; Edil, T. B.; Benson, C. H., & Tinjum, J. M. “Building environmentally and economically sustainable transportation infrastructure: green highway rating system.” *Journal of Construction Engineering and Management*, Vol 139, No. 12, May 2013, p. A4013006.

89. New York State Department of Transportation. NYSDOT Press Releases. Retrieved May 28, 2009 from State Transportation Commissioner Glynn Celebrates Earth Day: Announces GreenLITES Expansion & Adoption by Thruway and Bridge Authorities, 2009.

90. Illinois Department of Transportation, I. “I-LAST: Illinois-Livable and Sustainable Transportation Rating System and Guide.” Illinois Department of Transportation, Illinois, September 2012. http://www.idot.illinois.gov/assets/uploads/files/transportation-system/reports/desenv/enviromental/i-last%20v%202%2002.pdf

91. Blakeslee, G.; Loe, A.; and Hill, C. H. M. “Sustainable Transportation & Analysis Rating System (STARS): Pilot Plan Application Manual STARS-Plan Expert

Advisory Panel." North American Sustainable Transportation Council (STC), October 2012.

92. Barrella, E.; Amekudzi, A.; Meyer, M.; Ross, C.; and Turchetta, D. "Best practices and common approaches for considering sustainability at US state transportation agencies." In *Transportation Research Record 2174.* Transportation Research Board, National Research Council, Washington, D.C., 2010, pp. 10-18.

93. Evans, M. "Using Life Cycle Cost Analysis in Highway Project Development." Preliminary Investigation, Caltrans Division of Research and Innovation, California, November 2011. http://www.dot.ca.gov/newtech/researchreports/preliminary_investigations/docs/lcca_preliminary_investigation_11-29-11.pdf.

94. Hallin, J. *Guide for pavement-type selection.* Vol. 703. Transportation Research Board, 2011.

95. Demos, G.P. "Life cycle cost analysis and discount rate on pavements for the Colorado Department of Transportation." Report No. CDOT-2006-17, Colorado Department of Transportation, Colorado, October 2006.

96. Steyn, W.J.; Nokes, W.; Du Plessis, L.; Agacer, R.; Burmas, N.; Holland, T. J; and Popescu, L. "Selected road condition, vehicle and freight considerations in pavement life cycle assessment." International Symposium on Pavement Life Cycle Assessment, California, October 2014.

97. Deakin, E. "Sustainable development and sustainable transportation: strategies for economic prosperity, environmental quality, and equity." Institute of Urban & Regional Development, September 2001.

98. Liu, R.; Smartz, B.W.; and Descheneaux, B. "LCCA and environmental LCA for highway pavement selection in Colorado." *International Journal of Sustainable Engineering,* Vol. 8, No.2, March 2015, pp. 102-110.

99. Energy Information Administration (EIA). *Annual Energy Review.* http://www.eia.doe.gov/emeu/aer/pdf/pages/sec1_15.pdf.

100. Baker, R.; Ding, L.; Epps, J.; Estakhri, C.; Fry, G.; Geiselbrecht, T.; Goodin, G.; Hudson, J.; Lomax, T.; Morgan, C.; and Orsak, J. "TxDOT Administration Research: Tasks Completed FY2010." Report FHWA/TX-11/0-6581-T1-2, Texas Transportation Institute, Texas, February 2011.

101. Häkkinen, T.; and Mäkelä, K. "Environmental Impact of Concrete and Asphalt Pavements, in Environmental adaption of concrete." Research No. 1752, *Technical Research Center of Finland*, 1996.

102. Mroueh, U.; Eskola, P.; Laine-Ylijoki, J.; Wellman, K.; Juvankoski, E.M.M.; Ruotoistenm€aki, A. "Life Cycle Assessment of Road Construction. Highlights of Finnra Reports 2000." Finnish National Road Administration, Helsinki, Finland, 2000.

103. Zapata, P.; and Gambatese, J. A. "Energy consumption of asphalt and reinforced concrete pavement materials and construction." *Journal of Infrastructure Systems*, Vol 11, No. 1, March 2005, pp. 9-20.

APPENDIX A

Efforts of Integrating Sustainability into Different Pavement Life-Cycle Phases

Design Phase

Development of New Design Approaches and Tools for Pavement Projects. Generally, safety, efficiency, and sustaining fewer environmental impacts represent the most outstanding characteristics of a sustainable pavement. In addition, a sustainable pavement should satisfy conventional design requirements *[63], [64]*. The attempts to design and construct a sustainable pavement may be classified into three categories: 1) implementing a comprehensive LCA during decision-making processes, which require consideration of economic and environmental factors; 2) utilizing innovative design approaches and alternative materials to mitigate the environmental impacts in design and construction phases; and 3) creating more efficient standards and interpretation based on design parameters and performance.

The dominant method for designing pavement structure is the semi-empirical approach based on the AASHO road test conducted in the late 1950s. Currently, engineers seek to switch from this old design method to a mechanistic-empirical approach in designing pavement structure. The higher traffic load volume at the present compared to the 1950s coupled with a lack of accurate correlation to reflect different climatic and subgrade conditions present the main motivation for pavement engineers to develop and adopt a more efficient design methodology *[65]*.

Using the improved Mechanistic-Empirical Pavement Design Guide (MEPDG) helps enhance the resiliency and sustainability of pavements compared to the 1993 AASHTO design method. Therefore, different tools were developed based on the new mechanistic-empirical design method, in order to design a resilient and sustainable pavement structure by considering factors such as traffic, climate, and other design conditions, specific to the project. Using the MEPDG also allows practitioners to incorporate different types of materials within the pavement structure and to evaluate how different types of material influence pavement performance *[66]*.

Generally, most of the sustainability benefits defined by applying the MEPDG are long-term. The possibility exists that short-term advantages may be achieved in case of thin pavements, or pavement with various component properties. At present, the benefits from using the new design guide include: more accurate designs, better performance predictions, improved materials-related research, and a powerful forensic tool *[67]*.

Past research studies have demonstrated some of the superior advantages of the MEPDG. For instance, Cooper et al. used the MEPDG to predict the effect of WMA, reclaimed asphalt pavement (RAP), crumb rubber modifier (CRM), and sulfur additive on pavement performance

[64]. The researchers found that using sustainable mixtures such as RAP in HMA can improve pavement performance in comparison with conventional HMA. In order to compare WMA and conventional HMA, Buss et al. (2009) and Goh et al. (2007) also used MEPDG. Results indicated that the either the performances of WMA and HMA were comparable or WMA performance was somewhat superior to that of HMA *[68], [69]*.

Hu et al. 2010 used MEPDG to investigate the mechanical properties of typical Portland cement concrete in Iowa, required as input values in Pavement ME. The researchers found that although Iowa holds good documentation based on the compressive strength properties of PCC, additional data need to be documented to meet the input requirements of MEPDG *[70]*.

Many states are currently in the process of adopting Pavement ME in state specifications, in order to obtain a local, calibrated version of MEPDG. Indiana, Maryland, Minnesota, and New Jersey, as well as many other states have followed this approach. The Indiana Department of Transportation (INDOT) is one example of those states, which departed from the traditional design methods, and completely switched to MEPDG by mandating the design approach through projects funded by the federal government or state agencies since 2009. Furthermore, DARWin-ME software was calibrated by INDOT and added to the state's Design Manual. The software was explained to the practitioners through a workshop held in 2009 *[71]*.

Sustainable Pavement Design Practices. A sustainable design leads to fewer virgin materials utilization, minimal environmental impacts, and higher economic advantages, in addition to comparable performance. Generally, using materials with a higher cost and environmental impacts should be limited to the top layers near the surface, with low cost materials being used in lower layers, such as the subbase and subgrade layers. Longer life pavements present an innovative type of design, which would produce a more sustainable design by delaying and minimizing costs and environmental impacts associated with maintenance and rehabilitation activities necessary throughout a pavement service life. This methodology may increase cost and environmental impacts in the initial phases of the pavement life cycle, but a comprehensive LCA would indicate that this type of design would improve pavement sustainability in addition to enhance long-term performance. Recent developments in construction activities allow one to achieve specific design provisions and a knowledge of the basic properties of the materials used would contribute to the creation of designs that are more environmental-friendly *[66]*.

To improve pavement sustainability, LCCA, LCA, and sustainability rating systems may be utilized in the design phase of the pavement. By integrating these methods in pavement design, the benefits and drawbacks of each practice can be assessed prior to construction. In addition, these tools allow for a better consideration of factors such as smoothness, surface friction, noise, and storm-water management that play a significant role in pavement performance. Santos et al. (2016) applied an integrated LCCA and LCA analysis and a multi-criteria decision-making methodology to evaluate the sustainability of different pavement structures built using hot in-plant recycling mixtures, WMA, cold central plant recycling, and preventive treatments. Results indicated that HMA mixtures, which contain 30% RAP, provided the most efficient and sustainable pavement structure *[15]*.

A number of design alternatives may be considered to improve pavement sustainability. These solutions may include innovative design options such as the increase of recycled and local aggregate applications, fast track construction, storm-water management strategies, modular pavement systems (such as concrete paver blocks), use-phase impact consideration in the design phase, and noise-reducing surfaces *[72]*. Permeable pavement construction includes an open-graded aggregate structure that would facilitate the performance of a Low Impact Development (LID) drainage system. Using the LID solution in designing the drainage system has become a top priority for many highway agencies in large cities, such as the city of Seattle, as well as states such as Washington State.

Innovative Design Strategies to Improve Sustainability.

Life of Pavement: Constructing a pavement with long service life may be achieved by considering specific criteria in the design process. By utilizing long-life pavement strategies, the normal pavement life would increase from 30 to 60 years. Long-life pavement considerations in design are applicable for the design of new pavements, pavement rehabilitation projects, and pavements with inappropriate geometry *[4]*.

To design long-life pavement, an increase in the thickness of the layers, coupled with the use of higher stiffness materials, can improve the bending resistance and lead to a greater structural capacity. This approach can reduce the possibility of crack propagation in pavement structures. Furthermore, using recycled materials in the lower layers coupled with an increased thickness and the use of higher stiffness materials can be beneficial for a more sustainable design. In this venue, the environmental impacts and the cost of pavement projects would be initially higher as the result of applying design specifications of long-life pavements; yet, a comprehensive life-cycle assessment of this type of pavement would show a reduction in cost and environmental impacts. Long-life pavement can be applied to both asphalt and concrete pavement designs as discussed by FHWA *[4]*.

Long-Life Asphalt Pavement: Numerous sustainable advantages may be achieved by applying long-life asphalt pavement design:

- Selecting a material with higher quality and developing compaction efficiency would result in a higher bending resistance. The selection would make possible a reduction in the amount of mixture used in asphalt pavement. In this case, the cross-sectional area of the pavement can be reduced significantly, when compared to conventional types of design.

- The asphalt binder content and related environmental impacts can be reduced by using recycled aggregates from reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS). In addition, increasing stiffness and decreasing viscoelastic energy loss can be expected.

- An open-graded surface may be used for noise reduction as well as a gradual storm-water runoff. An open-graded surface may also operate as a layer to prevent propagation of top-down cracks.

- Using building and concrete pavement wastes in the base layer can be helpful to increase the sustainability of the pavement *[4]*.

By keeping the tensile strain to a minimum in a manner that avoids crack propagation in long life pavement, a perpetual pavement can be constructed. The cross-section of this type of long life pavement is illustrated in Figure 29.

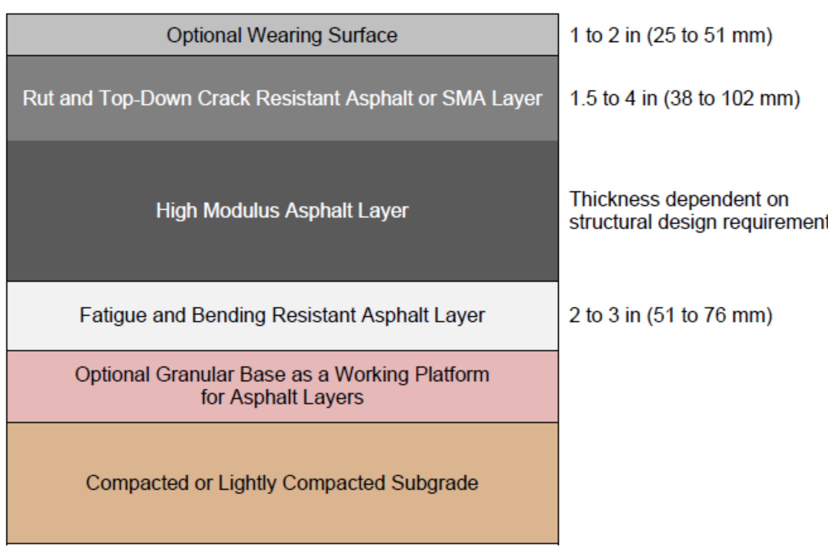


Figure 29
Cross-section of long life pavement *[16]*

The characteristics of the layers used in long-life pavements are explained below:

- The bottom layer of this type pavement is a crack resistant layer, which can endure not only the traffic load but also prevents cracking. Generally, there are two alternatives to build this crack resistant layer. The first is to increase the overall thickness of the pavement in a manner that allows the lowest tensile strain at the bottom layer. The second alternative is to apply a high level of compaction by keeping the percentage of air voids between zero to three, and then gradually adding the asphalt mixture. This type of bottom layer is called an asphalt-rich bottom layer *[4]*.

- Raising the "bending stiffness" is the most significant characteristic of the next layer. A stiff material, such as RAP, can be used to increase the stiffness of this layer. Furthermore, enhancing the compaction process in this layer can result in a crack-resisting material, which is beneficial for the pavement structure.

- The next layer, as the third one from the bottom, is designed to resist different types of pavement failures including top-down cracking, rutting, and low-temperature cracking. SMA and polymer-modified asphalt concrete are the types of material commonly used in this layer of the perpetual pavement. MEPDG may be used to determine the thickness of this layer.

- The next layer is an optional wearing surface, which functions as an abrasion-resistant layer. This layer consists of either a superior polymer- or rubber-modified, open-graded mixture, gap-graded mixture, or 1 to 2 in. (25 to 51 mm) SMA. Typically, this layer must be replaced when its effectiveness is reduced due to abrasion forced by vehicle interaction. This layer can also perform as a "noise reduction" layer *[4]*.

Using polymer-modified binder in the structure of long-life pavement can extend its service life. The type of material preserves the pavement surface from two major distresses: top-down cracking and rutting. Overall environmental impacts of long-life pavement are less than for normal pavement as it reduces maintenance and rehabilitation frequency, and thus, major impacts associated with these activities would be eliminated. On the other hand, utilizing polymer-modified binder in pavement can increase environmental impacts of the pavement due to GHG emissions in the production processes of polymer-modified materials. Therefore, before applying polymer-modified materials, the benefits and drawbacks of this type of material should be evaluated *[4]*.

Long-Life Concrete Pavement: Long life concrete pavements can either be constructed with JPCP or CRCP. Continuous surface restoration is the only maintenance activity required for this type of pavement, which enhances noise reduction and pavement smoothness. The service life of concrete pavement is usually between 35 to 60 years. The use of a thick concrete layer installed on non-erodible bases with adequately designed dowel bars and benefiting from stress-relieving design options such as tied concrete shoulders or widened slabs are among the alternatives that can allow meeting the objectives of a long-life concrete pavement *[4]*.

A long-life CRCP, which is fatigue resistant, is illustrated in Figure 30. Before applying CRCP, the expected benefits must be compared with the relative impacts of using steel reinforcement by applying an LCA analysis. Recycled materials and specially recycled concrete aggregate can be applied to the different layers of concrete pavements to lessen subgrade failure, preserve against frost action, and to improve subsurface drainage conditions. In addition, long-life concrete pavement usually includes some amounts of co-products, such as fly ash and slag cement, to enhance the durability and sustainability of long-life concrete pavement *[4]*.

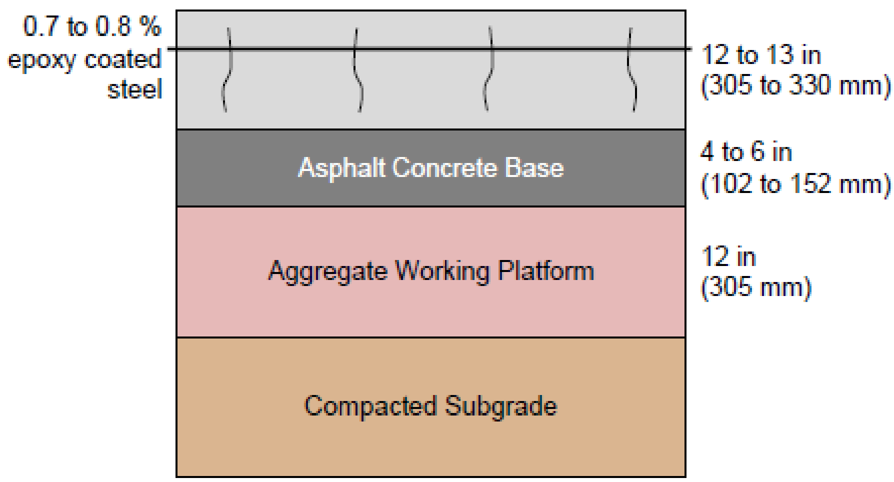


Figure 30
Cross-Section of a Long Life CRCP *[4]*

Future of Sustainable Pavement Design: With the ongoing research attempts to improve the sustainability of pavements, the future focus of research studies in this field may be expected in these areas:

Improving Material Characterization, Physical and Numerical Modeling in ME Design: One possible future improvement in mechanistic-empirical design may be the development of a material characterization test that would predict pavement performance. This can be done by applying characterization test results in appropriate physical and numerical models that are able to predict pavement performance. Accelerated Pavement Testing (APT) can provide some rapid feedback by performing large scale physical tests on actual constructed pavement. The result of this physical modeling must be compared with numerical models prediction results to ensure its validity. The most critical challenge in this area is in weighting the benefits and drawbacks associated with the use of innovative material and pavement structures, and also in training pavement engineers to implement design guidelines in an actual project. ME design methods are also required to be more developed in a manner that covers a variety of pavements structures *[4]*.

Improving ME Design Reliability: Information and methods for integrating within-project and between-project as-built variability into the design process should be improved *[73]*. The possible consequences of using recycled materials must also be considered to perform a more accurate comparison among the different design alternatives. ME pavement design should incorporate models for sustainable design considering environmental impacts. AASHTOWare Pavement ME design framework is proposed by FHWA for specific guidance and tools for sustainable pavement design *[74]*. Furthermore, these types of data provide a better prediction of potential rehabilitation activities *[4]*.

Incorporating the Environmental Impact Assessment Methods and Design Criteria: A modification of the analysis method can allow evaluating the environmental impacts of pavement processes. Therefore, by combining methods such as LCA, LCCA in tandem with the design process can result in a more efficient design. Yet, incorporation of the environmental benefits and impacts, together with cost analysis results and design requirements, may cause a complexity in pavement design processes. Therefore, to summarize and simplify these processes becomes the biggest challenge in this area. However, a simplification of the process may lead to an underestimation of substantial factors, which could result in an inaccuracy of the design. Defining the project objectives and adjusting the design criteria, and economic and environmental impacts of the pavement according to the specific project conditions would allow a better comparison among the different design alternatives. Selecting the most appropriate design alternative for various project delivery environments (DBB with alternative designs, DB, and DBM) should be developed through a multi-criteria decision-making process *[4,74]*.

Utilizing Innovative Materials: Use of recycled materials such as RAP, RAS, RCA, and SMA, besides applying co-products such as fly ash, is significantly increasing, due to a public who is encouraging to construct a sustainable pavement structure. Therefore, it would be beneficial to perform material characterization experiments to determine the quality of these new types of material. The relative design specifications must also satisfy the project objectives, while ensuring maintenance of the product price at the same affordable level.

Consideration of the Maintenance and Rehabilitation Process: Predicting possible rehabilitation activities and considering these in the design phase of the pavement can be an appropriate contribution in creating a more comprehensive LCA and LCCA analysis. Therefore, large scale physical testing, which validates numerical models, is necessary to compare between the different rehabilitation alternatives *[4]*.

Developing Smoothness Performance Models: The designers need a more comprehensive model to predict the smoothness of the pavement during the use phase. According to recent research, a smoothness performance model is one of the most outstanding items related to use phase, which must be considered in the design phase. Researchers are developing new technologies, such as a real-time measurement to predict the smoothness of the pavement during service life *[4]*.

Designing a Fully Permeable Pavement: Compared to current practices in managing storm-water problems on the pavement surface, constructing a permeable pavement is the best alternative for performance and cost analysis *[4]*.

Innovative Technologies: Adopting an innovative technology such as long-life pavement, rolling compacted pavement can enhance the sustainability of pavement as it requires lesser maintenance and longer life span, resulting in the reduction in the environmental impact. Different types of innovative technologies are briefly explained below.

Guidance and Outreach: Training and assistance materials to professionals and stakeholders on sustainable pavement program should be provided *[74]*. Online learning modules, instructor-led training and webinars should be provided for effective implementation of sustainable practices at all levels *[74]*.

Construction Phase

Methods to Enhance Pavement Sustainability during the Construction Phase. Table 22 presents promising strategies to enhance sustainability in the construction phase. These improvement strategies are designed based on four major goals, which are to lessen fuel consumption and emissions, to minimize noise, to hasten construction, and to control runoff, erosion, and sedimentation. These strategies can be applied to any type of pavements. Table 22 also presents economic and environmental benefits and the relative trade-offs for each strategy.

Table 22
Strategies to enhance sustainability in construction phase *[4]*

Objectives	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Reduce Fuel Consumption and Emission	Minimize haul distances	Reduced fuel costs	Reduced GHG emissions and air pollutants	
	Select	Reduced fuel		

	appropriate equipment type and size for the job	costs but may require capital investment	Reduced GHG emissions and air pollutants	
	Idling reduction	Reduced fuel costs; may require some capital investment to minimize idling	Reduced GHG emissions and air pollutants	Improved air quality
	Use alternative fuels	Varies	Reduced emission	Improved air quality
	Retrofit construction equipment, use hybrid equipment, or both	Will increase costs due to initial capital investment	Reduced GHG emissions and air pollutants	Improved air quality and may decrease construction related noise
Reduce Noise	Construction time restrictions	It may lead to reduction in construction productivity	May increase emissions if construction is prolonged	Less noise and may affect air quality
	Equipment maintenance or modification	Increased capital investment	No environmental impact	Less noise
Accelerate Construction	Effective traffic control and lane closure strategies	Reduced fuel costs for users and agency	May reduce traffic delays and associated emissions	Less traffic disturbance
	Establish performance goals and measures for work zones	Reduced fuel costs for users and agency costs	May reduce traffic delays and associated emissions	Less traffic disturbance
	Use project management software for construction sequencing and managing traffic delays	Reduced fuel costs for users and agency; extra effort for agency/contractor	May reduce traffic delays and associated emissions	Less traffic disturbance
	Implement intelligent transportation warning systems	Increased agency costs	May reduce traffic delays and associated emissions	Less traffic disturbance and improve work zone safety

Control Erosion, Water Runoff, and Sedimentation	Use perimeter control barriers (fences, straw bales, etc.)	May result in increased project costs	Reduced sedimentation, prevent degradation of water quality	May reduce potential water pollution
	Minimize the extent of disturbed areas	May result in increased project costs	Reduce disturbed areas	May reduce impact on surrounding residential areas
	Apply erosion control matting or blankets	May result in increased project costs	Reduced sedimentation	May reduce impact on surrounding residential areas
	Store/stockpile away from watercourse	No significant economic impact	May reduce potential water pollution	May reduce potential impact on area water

Strategies to Mitigate Emission and Energy Consumption in the Construction Phase. The rate of energy consumption and GHG emissions may be reduced in most of the construction categories. The most important categories to potentially enhance the sustainability in the construction phase include fuel consumption (moderate to major effect), electricity preservation (moderate to major effect), and choice of construction materials (not to minor effect). These categories are discussed in the following sections *[4]*.

Fuel Use. Fossil fuel burning is the main contributor to GHG emissions during the construction phase of a pavement. Therefore, selection of fuel type and equipment can influence sustainability considerably. Table A23 presents the emission factors in terms of GHG production (lb. of CO_2 per gallon of fuel) associated with the different fuel types. The amount of GHG reduction by using less fuel (3 and 10%), is also presented in Table 23.

Table 23
GHG reduction based on the fuel type *[4]*

Fuel Type	**Emissions, lbs. CO_2 per unit material**	**Estimated GHG Reduction Using 3% less fuel**	**Estimated GHG Reduction Using 10% less fuel**
Diesel	22.37 lbs. CO_2/gallon	600 million lbs. CO_2	2000 million lbs. CO_2
Gasoline	19.54 lbs. CO_2/gallon	186 million lbs. CO_2	621 million lbs. CO_2
Natural Gas	11.7 lbs. CO_2/1,000 ft^3	106 million lbs. CO_2	353 million lbs. CO_2

Operation Strategies to Reduce Fuel Consumption. Fuel consumption and corresponding emissions can be reduced by applying effective tactics such as reducing equipment idle time, preventing engine maintenance, and training the equipment operator. For instance, compared with being at high idle, Class 8 diesel engine consumption can be reduced by about 50% at low idle. Some of the best practices to reduce fuel consumption are summarized in Table 24. Furthermore, there are other options to reduce fuel consumptions such as smart selection of sites and plant location and choosing a smooth route for hauling the aggregates, which can help decrease fuel consumption and relative emission.

Table 24
Strategies to reduce fuel consumption during construction *[4]*

Operation Strategy	Costs	Benefits
Equipment idle reduction and control	Low administrative costs for training and tracking of idling Upfront investment if on-board idle reduction equipment1 is used (cost varying \$500-\$9000)[2]	Reduced PM, NOx, CO, and HC emissions Significant fuel savings Longer engine life and reduced maintenance costs
Engine preventive maintenance	Low administrative costs for tracking equipment maintenance needs	Reduced PM, NOx, CO, and HC emissions Significant fuel savings Longer engine life and reduced maintenance costs
Equipment operator training	Upfront investment for training programs	Reduced PM, NOx, CO, and HC emissions Significant fuel savings Improved operator efficiency
Construct choose and maintain stable haul roads	Upfront investment may be required to construct and maintain haul roads	Smooth haul roads improve fuel consumption Longer engine life and reduced maintenance costs
Select proper size and type of equipment depending on the production rate and road	No investment is required	Reduction fuel consumption Longer engine life and

conditions		reduced maintenance costs
Minimize haul distances by optimizing the plant and materials storage site location	No investment is required	Reduction fuel consumption

Fuel Use Strategies. Alternative fuels can decrease GHG emissions and are applicable for use in construction equipment, such as ultra low sulfur diesel (ULSD), biodiesel fuels, and compressed natural gas (CNG). ULSD is a type of fuel that has been processed through extra stages in order to separate the sulfur, which results in a less-emitting fuel. Biodiesel is another fuel alternative, which can be produced from soybeans, cottonseed, peanuts, and canola *[73]*. Biodiesel is typically mixed with ordinary diesel in different percentages such as B5, with 5% biodiesel, and B20, 20% biodiesel. CNG is another type of fuel that can be a suitable substitute for conventional fuels. CNG is produced by compressing natural gas, which is mainly dominated by CH4 (methane), to lower than 1% of the whole volume. This type of fuel is usually stored in specialized containers. A description of the different fuel alternatives is presented in Table 25.

Table 25
Description of fuel alternatives, costs, and benefits *[4]*

Fuel Strategy	**Costs**	**Benefits**
Ultra-low sulfur diesel (ULSD)	Higher price at the pump Lower energy content	Reduce PM and SOx emissions Reduce engine wear Increase oil change interval
Biodiesel (B5 and B20)	Higher price at the pump Increase NOx emissions Power loss and decreased fuel economy Degradation and wear in engine hoses or gaskets	Reduce PM, CO, and HC emissions Improve lubricity and reduce engine wear
Compressed natural gas (CNG)	Retrofit from gasoline and diesel vehicles is required Limited vehicle availability	Lower price at the pump Reduction in PM and greenhouse gas emissions

Strategies to Optimize Construction Equipment. Another alternative to mitigate GHG emission and to enhance sustainability in the construction phase is to improve available construction equipment. This process requires more funding, compared to previously discussed solutions. Upgrading older diesel engines and using grid electricity or hybrid equipment represent the most promising strategies to modify and improve construction equipment.

Installing a complementary device to retrofit construction equipment can reduce the amount of emissions. Using different types of treatment, such as diesel oxidation catalysts, diesel particulate filters, selective catalytic reductions, and exhaust gas recirculation can lead to a significant reduction in the amounts of PM, NOx, HC, and CO. Utilizing dual fuel systems or grid electricity can mitigate the rate of emission by about 15%. However, the percentage reduction may be affected by the source of grid electricity applied to the equipment *[4]*.

There are also other optimizing strategies to enhance the efficiency of vehicles and to reduce their relative environmental impacts. Optimizing strategies include modifying the type, size, and number of hauling equipment based on the rate of production, smoothness of hauling route, meeting plant production, hauling needs and paving activities, and preventing prolonged time of heavy equipment idling.

Air Quality Guarantee Practices in Construction Phase. In addition to the strategies that reduce emissions caused by construction vehicles, other practices can mitigate air quality problems related to the pavement construction phase. Some of the most common practices include water sprinkling and other dust control techniques, regular maintenance of dust collectors at concrete and asphalt plants. In addition, factors such as vicinity of residential areas need to be considered in plant and material storage selection.

Noise Reduction in Construction Phase. Reducing excessive noise caused by construction equipment and vehicles is another important factor for sustainability considerations in pavement construction. Construction noise can be reduced by limiting and mitigating excessive noise from haul vehicles, restricting plant and material storage location near light commercial and residential areas, integration of different noise-reducing devices, and adopting time-of-day construction restrictions *[4]*.

Effectual Traffic Control and Safety Consideration in Construction Phase. Construction activities impose some restrictions on highway services. Therefore, lack of effective traffic management and lane closure would cause traffic congestion leading to a higher amount of emissions, perturbation in the goods transporting system, fuel consumption raising, time wasting, and may jeopardize highway safety. Excessive emissions caused by traffic delays associated with construction phase activities depends on construction schedule and duration, roadway capacity, and traffic volume and control *[1]*. According to a Michigan study, the high amount of emissions caused by traffic congestion in the highways due to high Average Annual

Daily Traffic (AADT) was almost equal to the amount of emissions produced through the production stage.

An FHWA study that focused on different working zones through 13 states depicted that highways lose 60% capacity due to lane closures. According to the evaluated pavement projects, one experienced 33% reduction in capacity during nighttime closure while another experienced 58% reduction in capacity during nighttime closure. On average, highways experienced approximately 11 hours of closure during daytime, while the working zone occupied 6.8 mi of the highway for 125 days.

The following suggestions may be used as strategies to mitigate the impacts caused by work zone delays:

- Utilizing effectual lane closures strategies – Correct traffic management decreases the durations of work zone activity. A reduction in duration would decrease the amount of emissions and enhance the safety for both road users and construction workers. Some of the feasible strategies might be mentioned as adopting smaller lanes or shoulders, adopting weekend lane or road closures, and imposing lane rental fee, where the agencies would impose penalty because of closing down lanes as a motivation of speeding up the construction process.

- Defining performance aims and standards in work zones – Setting several specific objectives can clarify the direction that needs to be followed. Therefore, the highway agencies should define performance measures to be achieved. This might include items such as minimizing construction delays, reducing queue length, and reducing GHG emissions. This method was utilized by DOTs as well as European countries, such as Germany and the Netherlands. For instance, according to standards in the Netherlands, the overall work zone delay must be equal to 6% of the whole traffic delay, which is a lower number compared to 10% in the United States.

- Integrating analysis software related to lane closures through the planning phase – Applying management software can be helpful to analyze the influence of lane closure on emissions resulting from traffic congestion in the planning stage. Furthermore, the performance can be monitored during the construction phase, in order for feedback based on the progress. The sequence of the project processes can be determined by this type of analysis through the planning phase, with the goal of reducing relative impacts. QuickZone, CA4PRS, and DYNASMART-P are the available software used to analyze lane closures during the construction phase.

- Using ITS (Intelligent Transportation System) Technologies – Implementing this tool can assess, analyze, and adjust traffic speed and volume in a manner that decreases working zone delays by guiding drivers toward downstream traffic. Active message signs, a highway advisory radio, a radio channel, portable signs, a portable trailer, variable work zone speed limits, speed warning systems, and web cameras are the possible components of an ITS system. Furthermore, ITS systems can relieve traffic congestion in the working area by suggesting alternative routes. A study conducted in Michigan noted that traffic congestion was eased by incorporating an ITS technology and DLM (Dynamic Lane Merge) system. The DLM system is a type of alerting system, which informs the driver to merge into a relief lane before reaching a work zone area. In addition, oversight of the operation equipment must be in place to optimize the entry and exit *[4]*.

Storm Water Runoff and Sedimentation Control. Generally, a plan should be implemented to control sedimentation since pavements require extensive earthwork removal. In addition to the conventional practices to control storm water runoff and sedimentation, innovative methods have been suggested. For pavements that require extensive earthwork removal, it is recommend preserving existing vegetation cover in order to reuse it after earthwork completion. Although these plans are often applied in road construction projects, some amount of sedimentation remains, which may disturb the surrounding ecosystem, especially aquatic ecosystems.

According to various characteristics of different highway projects, the contractors should conduct an environmental investigation for each pavement project, in order to identify project limitations for applying different erosion and sedimentation control methods. The main objective for the environmental investigation is to avoid sediment transport from the construction site. However, controlling plans should not be time-consuming; otherwise, the consequences of traffic delays might impact sustainability. The following are the proposed practices to control sedimentation and erosion:

- Reduce the size of the impacted area by building natural cover that protects and preserves the whole area, and reinstating the affected environment;

- Develop erosion control action plan based on the conditions at the site, site topography, rate of water and chemical infiltration; these regulations can include various types of seeding and brushwood planting, and using erosion control blankets;

- Use sediment transport control such as perimeter controls, settling controls, and filtration controls whenever the vegetation option is not feasible;

- Reduce the gradient and size of the slope;
- Keep the standard distance from water sources (more than 40 ft.) *[4]*.

Construction Scheduling. The best way to achieve an efficient pavement rehabilitation plan and effectual traffic management is to utilize construction planning software tools, which provide the practitioners with vital information about the different steps of the construction phase. The main goal of most construction planning tools is to speed the construction phase so that the problems associated with the construction activities can be minimized. For instance, CA4PRS is a tool that can be used to evaluate different rehabilitation strategies and then select the most appropriate one, based on economic measures and sustainability considerations, such as excessive emissions resulting from traffic congestion. By assessing previous projects in which CA4PRS was used as a project planning tool, the study concluded that the traffic congestion caused by work zones can be decreased significantly. For instance, implementing an extended weekend plan for 55-hours was shown to cause a 40% rise in pavement productivity, in comparison with conventional nighttime closures. QuickZone and DYNASMART-P are two other tools that can be used as planning software *[4]*.

Managing Materials and Waste in Construction Phase: It is critical to manage construction waste and materials in a manner that would control pollution to storm water. The most critical areas that require an effectual management plan are polluted subgrade; vegetative waste and surplus paving materials; earthwork removal materials, drains, and culverts; waste piles; and other materials that can impact storm water quality. Furthermore, inadequate waste management practices should be considered, relevant to project conditions. Some of these considerations include the following:

- Any kind of chemical infiltration that can potentially contaminate the groundwater sources must be avoided by applying impermeable material.
- Cold mix asphalt stocks should be protected against rainfall infiltration.
- Soil stocks should be protected by a sediment barrier against rainfall infiltration.
- Hydraulic cement concrete and AC rubble stocks should be secured against rain infiltration.
- Segregation must be avoided during the period of storing and handling of aggregate *[4]*.

Use Phase

There are some design factors that relatively influence the environmental impacts of the pavement during the use phase. Two important design factors must be considered to obtain a more sustainable design. The first one is smoothness, since the environmental impacts of the pavement can be significantly reduced by preserving the smoothness of the pavement during the entire life-cycle of the pavement. The second factor is the life span of the pavement, which reduces the life-cycle cost of the pavement. In addition, the pavement life span decreases social and environmental impacts related to materials production, construction, and periodical maintenance and rehabilitation. The project condition is the factor that determines which design factor is more important. For instance, if the project is a high-volume traffic pavement system, smoothness consideration is the dominant design factor. On the other hand, when the pavement is to be designed for a low volume traffic route, material production and construction would be the dominant design factor influencing environmental impacts *[4]*.

Construction Technologies Adopted by State DOTs for Flexible Pavements

The increasing price and lack of availability of the construction materials concerns highway agencies and state DOTs. These increasing concerns on environmental impact has led to the adoption of different alternatives which would reduce the negative environmental impact and less consumption of resources. Therefore, an alternative practice such as use of recycled hot mix asphalt, asphalt shingles, aggregate base stabilization, and treated subgrade are widely used in different states *[75]*. Use of these alternatives not only lowered the high consumption of resource, and energy, it reduced the construction price to a significant amount. The use of recycled materials in pavements can be tracked back to the 1970's *[76]*. Since then the consumption of the asphalt binder and the road oil has been decreased and till today the level of the total energy consumed using the same materials has returned to the consumption level of 1970s.

Use of recycled asphalt pavement (RAP) in the HMA surface course and the lower levels of pavements is increasingly rapidly. To date, about 75% of all state standard specifications allow at least 10% RAP in HMA surface course mixes and allow for greater than or equal percentages lower levels of pavement; i.e., base, subbase, etc. *[75]*. Using RAP as a base reduced the rate of structural deterioration due to the increased load carrying capacity of base in comparison to the traditional aggregate base.

Recycled asphalt shingle (RAS) is another alternative to the transitional mix design. It reduces use of the asphalt binder significantly, as the asphalt content may be 18% to 40% (varies depending upon sources). This will reduce the cost and emissions associated with the production of asphalt and lessen the burden to the environment. Currently 14 state standard specifications or special provisions allow up to 5% manufactured or tear-off shingles in HMA.

Cold in-place recycling is another widely used alternative. Nationwide, it has been employed on four or more projects in 18 states, where 12 states have standard specifications or special provisions for the same *[77]*. Hot in-place recycling has been used by 10 states for different projects and for 22 states it is in experimental phase *[78]*. The main advantage of this alternative is that it reduces the amount of the recycled amount to be hauled to the job site.

Stabilization and treatment to base/subgrade has proved to be good alternative in comparison to the traditional methods. Benefits can be seen in context of both aspects; i.e., economic and environmental. These structures have increased the coefficient of layer and hence provides the more stability to the overlying layer and may reduce the pavement structural deterioration. Structurally sound pavement calls for lower frequency of construction of HMA overlay which will reduce the economic cost and energy consumption. In addition, lesser the roughness index lower will be the fuel consumptions and emissions in use phase. States such as Colorado and Michigan have given credit to the improved load carrying capabilities of recycled aggregate base by using emulsion stabilized aggregate base, cement stabilized aggregate base and cement treated base instead of normal aggregate base.

APPENDIX B

Sustainability Rating System

This section discusses the following rating tools: Greenroads, ENVISION, Green Highway Partnership (GHP), INVEST, GreenLITES, I-LAST, BE2ST-in-Highways, as well as related program applications for different states.

Greenroads

Greenroads is a project-based rating system in which a collection of best sustainable approaches is used to design and build new roads or to redesign and reconstruct rehabilitated roadways. Notably, planning (e.g., alternative selection, etc.) or operations (e.g., vehicle fleet mix, fuel efficiency, etc.) components are not within the scope of a project-oriented metric. Greenroads are perspective qualitative methods as its ratings system is assigned based on the developed sustainable practices i.e. ratings are given only if specific requirements are met.

The adopted metric assigns specific points for different types of sustainable practices to measure sustainability in roadway design and construction. This quantification can be used to define the project contribution to road sustainability, to communicate sustainable project attributes to stakeholders, and to award certification based on reaching a minimum number of points *[79]*.

Project requirements and voluntary credits are the main categories of sustainability best practices in Greenroads. According to the impact of the practice on the sustainability of pavements, points from 1 to 5 are given. There are 37 voluntary credits with a total sum of 108 points. Agencies are also able to apply their own voluntary credits, which adds up to 10 more points, thus making the total 118 points *[80]*.

Project Requirements. In order to be considered in Greenroads, specific requirements should be met. Only projects that meet all the requirements and achieve extra voluntary credit points are qualified to receive the Greenroads certification. Each requirement is defined, based on the five main credit categories, and would be explained in the associated category. However, some of these requirements might not be applicable given the specific conditions of the project *[81]*.

Voluntary Credits. Besides the requirements defined for Greenroads projects, there are many voluntary credits that can be achieved by different projects. Based on how each credit category affects sustainability, credit points from 1 to 5 can be awarded. Upon verification that an amount of credit points has been achieved, the certification level can be awarded.

A vast range of activities such as cultural development, multimodal access, pavement materials, and safety are included among the voluntary credits. In fact, there is no possibility for a project to earn all the credit points. Therefore, the Greenroads program provides the project stakeholders with a variety of different categories, so that all the projects could achieve the minimum requirements, as well as the Greenroads certificate. Greenroads developers are modifying the program in a manner that all the projects, from basic preservation overlays to large, multi-billion-dollar corridor projects, are considered *[81]*.

Certification Levels. Different certification levels are awarded based on the total level of points earned by the project. In other words, the project needs to satisfy all the required rules and earn enough voluntary credits out of the 118 possible credit points. Generally, the Greenroads team awards four different certification levels, see Figure 31:

- **Certified:** All Project Requirements + 32-42 Voluntary Credit points (30-40% of total);
- **Silver:** All Project Requirements + 43-53 Voluntary Credit points (40-50% of total);
- **Gold:** All Project Requirements + 54-63 Voluntary Credit points (50-60% of total);
- **Evergreen:** All Project Requirements + 64+ Voluntary Credit points (>60% of total)

Figure 31
Levels of certification graphics in Greenroads *[81]*

System Boundaries. The Greenroads system can be utilized in construction and rehabilitation of highway projects. Design phase and construction activities such as material transportation, Portland cement concrete (PCC) and hot mix asphalt (HMA) production are within the scope of Greenroads. In the applications of Greenroads, some factors should be considered:

- ***Roadway Planning***. The credit point system of Greenroads does not comprehensively evaluate all the aspects of complicated decisions such as the selection of location, type, timing, or feasibility of the project. Therefore, these decisions are out of the scope of the Greenroads rating system.

- ***Material Manufacturing and Refining.*** The Greenroads system does not consider improvements in activities such as the asphalt manufacturing process. Such activities are only considered in the Life-Cycle Inventories (LCI) or the Life-Cycle Analysis (LCA).

- ***Structures.*** Non-material information, such as the structural design and geotechnical information of structures (bridges, tunnels, walls, etc.) cannot be included. The only part that the Greenroads system considers is the material part.

- ***Path and Trails***. Only the paths that are directly related to the road, such as a sidewalk or bicycle path, are considered in this system. The other paths and trails, which are not dependent on the main roadway, such as conversion of a rail right-of-way to bicycle path are not considered by the Greenroads system.

- ***Maintenance and Preservation***. These two activities play a significant role in enhancing the sustainability of the pavement and would be taken into account during a detailed evaluation of the life cycle of the roadway. However, these items alone cannot be judged until after the project completion, Therefore, they are evaluated based solely on an implementation plan for the future *[81]*.

Philosophy of System. Greenroads considered the following factors during development of the program:

1. Being easy and understandable is the first parameter that was considered. Audience with low level of pavement construction knowledge should understand the general concepts and ideas. Although the voluntary credit points originate from complex ideas, the notion is simplified to be understandable.

2. Empirical evidence and utilization of existing assessment tools are two significant items required in setting up project requirements and voluntary credits. These two categories should be based on the prevalence of empirical evidence and assessed by existing evaluation techniques.

3. Selecting the appropriate corresponding points with respect to characteristics of each category such that the credit points are assigned in accordance with the magnitude of the social, economic, and environmental impacts of each item.

4. Flexibility is very important for the Greenroads system. The program should involve a wide range of voluntary credits, so that small scale projects like preservation overlays, as well as large scale projects, such as development of a new corridor, can achieve some level of certification.

5. Continuous development of the program was considered by the developers. The program should have implemented feedback from the practitioners who applied the Greenroads system.

6. Minimal bureaucracy. The process of receiving certificates should be easy, inexpensive, less time consuming, and feasibly accomplished with the existing document.

7. Being above the requirements. The Greenroads program must encourage the practitioners to design and construct the projects to go beyond the minimum requirements. This is to prevent the Greenroads program from becoming a marketing tool *[81]*.

The Structure of Greenroads. According to the Greenroads approach, a sustainable road is defined as a road that has the capacity of supporting natural laws and human values *[81]*. The "natural laws" include three fundamental rules that must be considered to sustain the ecosystem of the earth:

- Do not extract substances from the earth at a faster pace than their slow redepositing and reintegration into the earth.

- Do not produce substances at a faster pace than they can be broken down and integrated into nature near its current equilibrium.

- Do not degrade ecosystems, because our health and prosperity depend on their proper functioning.

The concept of "Human Values" is based on two parameters of equity and economy. The equity concept is defined as nine basic needs that must be satisfied: subsistence, protection, affection, understanding, participation, leisure, creation, identity and freedom *[80]*. Economy is defined as manufactured, financial, and human management. Based on this interpretation, economy can refer to financial matters of a project but it can also reflect forest resources management and carbon cap-and-trade plans *[81]*.

Benefits. According to the Project Requirements and voluntary credits, the Greenroads system determines relative benefits of the project. The benefits are efficiently stated in an easy language in order to be understandable. The following list contains the benefits given, based on the project qualification *[81]*:

- Reduce water use;
- Reduce fossil energy use;

- Reduce raw materials use;
- Reduce air emissions;
- Reduce wastewater emissions;
- Reduce soil/solid emissions;
- Optimize habitat and land use;
- Improve human health and safety;
- Improve access and mobility;
- Improve business practice;
- Increase life-cycle savings;
- Increase life-cycle service;
- Increase life-cycle awareness;
- Increase life-cycle aesthetics;
- Create new information; and
- Create energy.

Greenroads Shortcomings. There are various rating systems available for construction engineers, but the one that gained more attention and got more credit is the Leadership in Energy and Environmental Design (LEED) developed by the U.S. Green Building Council's (USGBC). The LEED system is used to rate sustainable buildings. The practical usage of LEED provoked some criticism on its weakness points, such as using credits that are not weighted to represent the environmental impacts and the high cost of the projects. Therefore, the Greenroads rating system is built based on the evaluation of the strengths and weakness of LEED by having the credits, which are proportional to the impacts, and having less bureaucracy; these are among the principles of Greenroads *[81]*.

The Greenroads evaluation system is applied to the design process and construction activities within the working area, but exclude the manufacturing process, as well as the use and maintenance phase. Sustainable design, materials and resources, storm-water management, energy and environmental control, construction activities, and innovation are the six categories upon which the Greenroads system awards credit. Each of these categories contains a number of credits. A credit is a type of design or a construction decision or activity that can enhance the sustainability of a roadway project. Credit weighting is done based on the magnitude of the impact and the duration of that impact. Generally, the roadways with a short-term impact are granted 1 credit and the long-term impact roadways are granted 2 credits. Further, 3 credits or more can be assigned to those impacts that last until the end-of- roadway life cycle *[81]*.

ENVISION

ENVISION was developed by the Institute for Sustainable Infrastructure (ISI), with the cooperation of the Zofnass Program for Sustainable Infrastructure at the Harvard Graduate School of Design. This rating system is used to rate infrastructure such as water storage and treatment, energy generation, landscaping, transportations, and information systems. The system was supported by three organizations: The American Public Works Association (APWA), the American Society of Civil Engineers (ASCE), and the American Council of Engineering Companies (ACEC). ENVISION is a performance based qualitative assessment method as it recommends achieving certain sustainability needs/levels doesn't specifies on what methods and technologies to be used i.e. it says to reduce GHG emissions and gives credits if those are met but doesn't specifies any methods/techniques to be used as in greenroads.

ENVISION has 60 sustainability credits arranged into five categories: quality of life (13 credits), leadership (10 credits), resource allocation (14 credits), natural world (15 credits), and climate and risk (8 credits). The program encourages the use of life-cycle analysis in planning, designing, construction, and operation to improve project sustainability performance by means of a two-process evaluation system. The first stage involves a self-evaluation process, and the second one involves a third party verification. ENVISION awards four certificates:

- Bronze award (20% of total points achieved);
- Silver award (30% of points achieved);
- Gold award (40% of points achieved); and
- Platinum award (50% of points achieved).

ENVISION is heavily weighted towards Natural World and Resource allocation categories, i.e., 32% and 29% of the credits respectively available under this system. Quality of life, leadership, and climate are rated for 18%, 13% and 8%, respectively *[82]*. ENVISION was pilot-tested in Colorado. This was inclusive of four projects: The Academy/Woodmen Road interchange in Colorado Springs, Little's Creek in Littleton, Gold Camp Tunnel in Teller County, and the Aspen Rio Grande Recycling Project *[83]*.

ENVISION was used in different projects across the U.S., such as a power project in Holland, Michigan, that scored a platinum rating. The Los Angeles County Board of Supervisors, together with the new Sustainability Chief Officer, also adopted the use of ENVISION for county infrastructure projects. Likewise, the Nashville Metropolitan Government West Park Equalization Facility, a joint project owned by the Metro Nashville Water Services Department

(MWS) and the Metro Nashville Parks and Recreation Department (MPR), recently earned the ENVISION Platinum award for sustainable infrastructure, the highest rating of the ENVISION system. Similarly, a Vancouver Road Realignment won the First ENVISION Platinum Transportation Project award; the Vancouver project was the first transportation project to receive the Institute for Sustainable Infrastructure's ENVISION Platinum Award for a sustainable infrastructure rating system. Likewise, the Sun Valley Watershed Multi-Benefit Project, a project built to manage storm water, has also earned the ENVISION Platinum Award. The project offers flood protection, better watershed health, more open space, and an increased wildlife habitat. Similarly, the South Los Angeles Wetland Park in Los Angeles, California, won a Platinum Award.

Other projects, such as Atlanta's Historic Fourth Ward Park project, recently received the Sustainable Infrastructure ENVISION rating system's Gold Award. Tualatin Valley Water District's Ridgewood View Park Reservoir and the Pump Station in Portland also recently received the Institute for Sustainable Infrastructure's ENVISION rating system's Gold Award. This was the first ENVISION award project in Oregon. Likewise, Portland General Electric's Tucannon River Wind Farm project received the Institute for Sustainable Infrastructure's (ISI) ENVISION sustainable infrastructure rating system's Gold Award. This was the first energy project to receive an ISI ENVISION-verified sustainable infrastructure award in North America *[80]*.

Other silver winning projects include the Tarrant Regional Water District (TRWD) of North Central Texas, which won the ENVISION Silver award for its Line J, Section 1 Pipeline project; the project has the oversight of a 2-mile, 108-inch diameter pipeline, which delivers water to encounter the growing future demands of people in North Central Texas. Other award-winning projects include: A wastewater treatment plant renovation in Brooklyn, New York. This is the seventh infrastructure project in North America to receive an ENVISION sustainability designation from the ISI. The main advantage of ENVISION is that the system incorporates the largest number of project infrastructures. The model may be applied to water treatment and storage systems, transportation, energy generation, landscaping, and information systems *[80]*.

Green Highway Partnership (GHP)

The Green Highway Partnership (GHP) was created based on three fundamental aims: project environmental streamlining, safety, and congestion reduction. GHP carries a significant role in guiding the road construction industry toward a "green highway" system. This improved environmental sensitive project can be achieved by applying the environmental regulation of the roadwork into the desired project. Forty-five organizations consisting of seven DOTs have joined the partnership, following the first meeting between FHWA and US EPA's Mid-Atlantic Region 3 *[84]*. This is a perspective qualitative method as it defines a specific requirement to be met.

There are innovative and interesting features in the GHP. The partnership concentrates on environmental standards, citizen participation, and the requirements of construction companies. The Green Highway Partnership assumes that green planning for roadways should be developed in order to involve all the aspects that would be influenced by pavement construction. Furthermore, continuous monitoring and evaluation of the system is one of key features of GHP, which is unique to this method *[84]*.

Initially, the GHP started with implementing the pilot projects, which were beneficial in identifying green highway technology. Then, the GHP developed a comprehensive method to evaluate the environmental conditions of the roadway, as well as environmental impacts weights to incorporate the minimum requirements with efforts that concentrated on going beyond the rules, initiated by the Maryland State Highway Administration *[84]*. The intent is to preserve the historical face of the project area, by linking regional transportation plans with local land use, by using recycled materials, and by reducing any disturbance to the ecosystem caused by construction processes through wildlife conservation plans *[84]*.

FHWA Sustainable Highways Self-Evaluation Tool (INVEST)

The INVEST evaluation tool was developed by the FHWA to allow agencies to consider sustainability during highway design and construction. The original intention of developing this evaluation tool was to promote sustainability considerations through the agencies and stakeholders in the transportation field. The use of this program is totally voluntary, and there is no plan toward making the program compulsory *[85]*. This is a performance based qualitative method as it evaluates the tool used to address sustainability and does not provide specific set of rules to be followed.

System Planning (SP), Project Development (PD), and Operations and Maintenance (OM) are three modules upon which the INVEST is based. Each of these modules may be assessed individually with respect to an independent collection of criteria. This program consists of 60 criteria. System planning is the first step to determine the projects contribution to the safety, capacity, access, operations or other key features of the system *[85]*. This module consists of 16 criteria plus one bonus criterion, which is assessed based on the score achieved by means of the main criteria. There is one scorecard allocated to this module that covers the whole scoring criteria. The next step is the project development phase which plans, designs, and builds the special projects conceptualized and designed in the System Planning processes. The project development module includes 29 criteria and six scorecards to assess the different phases of the project from planning to construction. Paving, Basic Rural, Basic Urban, Extended Rural, Extended Urban, and Custom are listed as the scorecards of this module. The last scorecard (Custom) makes the program flexible in order for the program to be adjusted to a project, which may not otherwise fit to predefined scorecards. The INVEST program defines the following six scorecards:

- Paving – used in projects that encompass pavement preservation, restoration projects that prolongs pavement service life and improve ride quality and safety, restoration projects that increase pavement structural capacity, and spot safety. This scorecard is applicable to paving projects in rural and urban areas.

- Basic Rural – used in small reconstruction or bridge replacement projects, which do not increase the capacity of roadways in rural areas.

- Basic Urban – used in small reconstruction or bridge replacement projects, which do not increase the capacity of roadways in urban areas.

- Extended Rural – used in new pavement projects, structure projects, and large reconstruction projects that increase the roadways capacity in rural areas.

- Extended Urban – used in new pavement projects, structure projects, and large reconstruction projects that increase the roadways capacity in urban areas.

- Custom – used in projects that cannot be sorted in any of the above categories. Custom scorecard allows the user to define a new set of criteria, which fit the project conditions. No achievement level is awarded to a pavement according to the custom scorecard.

Figure 32 illustrates the different criteria that fall in each scorecard, based on the project type. As previously mentioned, the custom scorecards that consist of 19 criteria permit the user to choose other desired criteria, in order to construct a self-evaluation assessment tool for a specific type of project. In a review conducted by AASHTO, the main critique of INVEST focused on a double counting of some credits, caused by a concept overlap in each module. Another concern was that some of the credits do not consider all aspects of sustainability, such as environmental, economic, and quality of life *[85]*. This statement holds true for other green rating systems as well.

The Washington State Department of Transportation (WSDOT) is interested in evaluating INVEST. For this purpose, WSDOT prepared a proposal which involves two main goals: 1) to enhance the sustainability practices at WSDOT, and 2) to provide a productive feedback on each module for FHWA to enhance INVEST so that the program could be applied for planning studies and project development processes. The Washington State Department of Transportation released a program called "Moving Washington," in which a move toward the triple bottom line of the sustainability was sought. WDOT is also interested in INVEST, because the features of WDOTs plan are also reflected in INVEST program results. Three corridor planning projects were selected for evaluation by the system planning module; the SR 520 Bridge and HOV Program was selected to be assessed by the project development of the INVEST program. The results of the INVEST evaluation indicated that the program required some modifications to address all aspects of sustainability *[86]*.

Project Development by Criteria Scorecard

	Paving	Urban Basic	Urban Extended	Rural Basic	Rural Extended	Custom Core Criteria[1]
PD-1 Economic Analyses			√		√	
PD-2 Life-Cycle Cost Analyses	√	√	√	√	√	√
PD-3 Context Sensitive Project Development		√	√	√	√	√
PD-4 Highway and Traffic Safety	√	√	√	√	√	√
PD-5 Educational Outreach	√	√	√	√	√	√
PD-6 Tracking Environmental Commitments	√	√	√	√	√	√
PD-7 Habitat Restoration		√	√	√	√	√
PD-8 Stormwater		√	√	√	√	√
PD-9 Ecological Connectivity			√	√	√	
PD-10 Pedestrian Access		√	√			
PD-11 Bicycle Access		√	√			
PD-12 Transit & HOV Access		√	√			
PD-13 Freight Mobility			√		√	
PD-14 ITS for System Operations		√	√		√	
PD-15 Historical, Archaeological, and Cultural Preservation		√	√	√	√	√
PD-16 Scenic, Natural, or Recreational Qualities			√	√	√	
PD-17 Energy Efficiency		√	√	√	√	√
PD-18 Site Vegetation		√	√	√	√	√
PD-19 Reduce and Reuse Materials	√	√	√	√	√	√
PD-20 Recycle Materials	√	√	√	√	√	√
PD-21 Earthwork Balance			√		√	
PD-22 Long Life Pavement Design	√	√	√	√	√	√
PD-23 Reduced Energy and Emissions in Pavement Materials	√	√	√	√	√	√
PD-24 Contractor Warranty	√	√	√	√	√	√
PD-25 Construction Environmental Training		√	√	√	√	√
PD-26 Construction Equipment Emission Reduction	√	√	√	√	√	√
PD-27 Construction Noise Mitigation		√	√			
PD-28 Construction Quality Control Plan	√	√	√	√	√	√
PD-29 Construction Waste Management	√	√	√	√	√	√
Total Number of Criteria in Scorecard	12	24	29	21	25	19

1 – Indicates the core criteria that must be included in the custom scorecard. The user may choose as many additional criteria as desired.

Figure 32
Scorecards based on different criteria *[85]*

Arizona Evaluation of INVEST. The Arizona Department of Transportation (ADOT) developed a comprehensive plan to implement all three modules of INVEST self-evaluation tool to enhance the sustainability of pavements in the State. System Planning, Project Development, and Operation and Maintenance are the three modules of the INVEST program. ADOT conducted the following five main activities *[87]*:

1. Scored over 50 individual transportation projects with INVEST PD and developed recommendations for improvements to ADOT practices as a result of the INVEST evaluations.

2. Integrated recommendations and sustainability concepts from INVEST into ADOT manuals and guidance, specifically, its MPO/COG Manual, ADOT Complete Transportation Guidebook, and Standard Specifications for Road and Bridge Construction.

3. Initiated usage of INVEST to evaluate alternatives in the environmental review process for Interstate I-11, a major project to build a new north-south Interstate.

4. Conducted sustainability training using INVEST with internal ADOT departments, external local public agencies such as the cities of Sedona and Flagstaff, and with students and professors in a partnership with Arizona State University.

5. Developed an ADOT Sustainability Award program to recognize ADOT projects and project managers that went above and beyond in sustainability efforts, as measured by INVEST score, best management practices, and collaboration.

The project development part of the INVEST program involves early project planning, alternatives analysis, environmental documentation, preliminary and final design, and construction. According to the type and the location of the project, INVEST provides the users with 5 scorecards and 29 related criteria. The custom scorecard consists of 19 main criteria and some selective criteria that the user would choose according to the project specifications. ADOT applied two scoring methods, parallel to each other. Both one on one scoring approach and the project management team scoring are utilized by ADOT *[88]*.

ADOT has enhanced and organized the project development process. The Project Management Team (PMT) in ADOT believes that the project development process must be started before the construction phase. Therefore, some preliminary considerations such as traffic, safety, and environmental issues must be taken into account *[86]*. When the need arises to add a lane in a highway due to high traffic volume, ADOTs Regional Traffic Engineer, a maintenance foreperson, the District Engineer, and a city or county engineer hold a meeting to generate the problem statement. Generally, the district level is where most of the projects are started *[87]*.

Since there are usually more projects identified than money to build, a process of prioritizing each project, determining the overall scope, and estimating the costs is initiated during the planning phase. During the planning phase, the initiation of a study reviews several engineering alternatives and environmental elements in details; results of the study are often shared at a public hearing. After the public hearing, a design phase and an environmental review process will run concurrently. The project then advances through the design, environmental, and subsequent pre-construction phases *[87]*.

Before a project can move into construction, the project must be included in the Five-Year Highway Construction Program and have funding set aside. The Five-Year Highway Construction Program is reviewed and ultimately approved each year by the State Transportation Board. In addition to approving the Five-Year Highway Construction Program, the State Transportation Board officially awards a contract to the contractor who was successful in the bid process, or in some cases, is most qualified to complete the project *[88]*.

The next step is to build the project. The contractor moves on to the project site and an ADOT Construction Field Office oversees the construction work. Their job is to inspect the work, pay the contractor accordingly, and ensure that the project serves the public as intended *[87]*. The final steps are to open the project to the public and to maintain the project or facility to perform as needed.

BE2ST – University of Wisconsin

The sustainability rating system, entitled Building Environmentally and Economically Sustainable Transportation (BE2ST), was developed by the University of Wisconsin. BE2ST is designed to produce a quantitative, comparative analysis to rate different sustainable practices in pavement construction. By coupling LCA/LCCA analysis with the performance analysis of MEPDG, this rating approach addresses pavement performance in depth. In contrast with the other methods based on the random scoring systems, this approach applies a number of evaluation tools such as LCA, LCC, and MEPDG. In addition, BE2ST is positioned to consider 3Rs system (Reduce, Reuse and Recycle) and seeks to reach a particular amount of reduction in environmental and human resource impacts. Greenhouse Gas Emission, Energy Use, Water Consumption, Material Reuse/Recycling, Human Health/Safety are the six categories on which BE2ST concentrates to mitigate the consequences of paving construction *[88]*. BE2ST recommends to consider 3Rs system and rating approach is based upon the same, therefore, this is a perspective based qualitative system.

Selecting Criteria and Targeting Values. A sustainable highway construction typically consists of two major ingredients: the criteria and the target value of each criterion. For this purpose, it becomes necessary to gather all the stakeholders to regard the different expectations valued for consideration. During the meeting of the stakeholders in Wisconsin, six criteria were selected to construct the sustainability vision of this approach. Global Warming Potential, Energy Use, Water Consumption, Material Reuse/Recycling, and Human Health/Safety were the criteria selected by this group *[88]*.

The target value of each criterion was determined, based on future needs and requirements. According to the 2002 Census, the share of the road construction industry drawn from the whole industry Mg-CO_2 production, was up to 6.8%. Since there is a need to reduce 227 Mg-CO_2 per km of pavement construction (based on Carpenter et al. 2007), a 20% reduction, which is equal to 192 Mg-CO_2 reduction, may be reached by applying this approach. By applying some minor amendments, achieving 227 Mg-CO_2 reduction is reachable *[88]*.

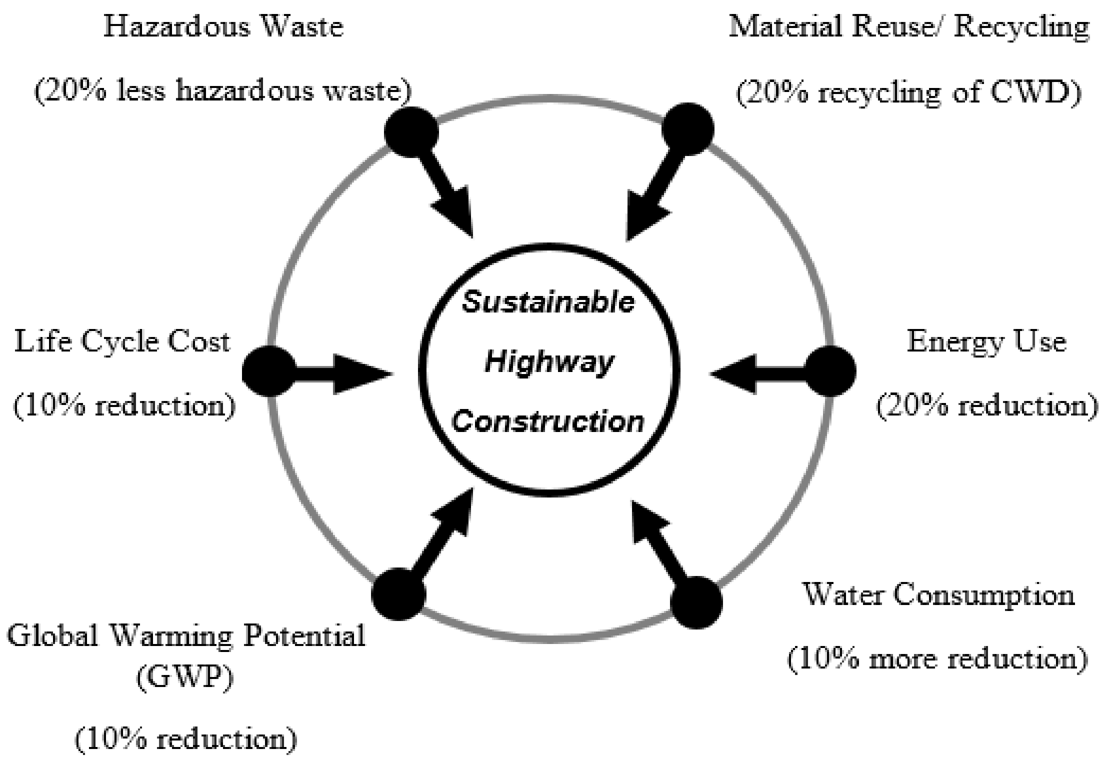


Figure 33
The target value of each design criterion *[88]*

Criteria Weight Determination. Three types of weighing system may be applied in this approach to each selected criterion: 1) Assigning equal weight to all criteria; 2) Assigning the weights based on the project specifications; and 3) Assigning weight based on the stakeholder's agreement. The Analytical Hierarchy Process (AHP) may be used to determine the appropriate weighing values in the second and third types of weighing system *[88]*.

Creating a Typical Conventional Design Concept. Through this step, the difference between a conventional design concept and the one which the sustainability practices apply, is used to indicate the measure of sustainability of the project. Therefore, the conventional design concept should be prepared in a way that no sustainable practice would apply during the life cycle of the pavement *[88]*.

Different Layers in Rating Process. There are two main layers involved during the process of achieving a quantitative rating, based on each design type. The first layer is called Mandatory Screening Layer, which consists of two main indicators: Regulatory/Social Indicator and Project Specific Indicator. Regulatory/Social Indicator and a Project-Specific Indicator are used to evaluate the compliance of a project to the laws, regulations, local decrees, and required project specifications in the Mandatory Screening Layer. The criteria that satisfy the public demands, local official provisions, and project specifications, must be included in regulatory/social indicator. For example, an environmental impact statement, a requirement for federal funds, is categorized as the regulatory indicates. Cultural and aesthetic concerns such as protecting ancient relics can be addressed by the project-specific indicators. Every project needs to be monitored through this process; otherwise, further evaluation with judgment indicators is not feasible *[88]*.

Two environmental and economic indicators are used to evaluate the sustainability and performance of the pavement. In this phase, the frequency of pavement rehabilitation would be determined, based on road roughness changes, which must be monitored through the pavement performance analysis period *[88]*. FHWA stated that since the IRI terminal level is reached at 2.7 m/km, which level becomes a reliable document to consider whether the pavement has reached the scheduled maintenance and rehabilitation. MEPDG, the software utilized by BE2ST, provides an approach to predict pavement performance. Figure 34 illustrates a schematic of the manner in which BE2ST rates the different alternatives and inputs *[88]*.

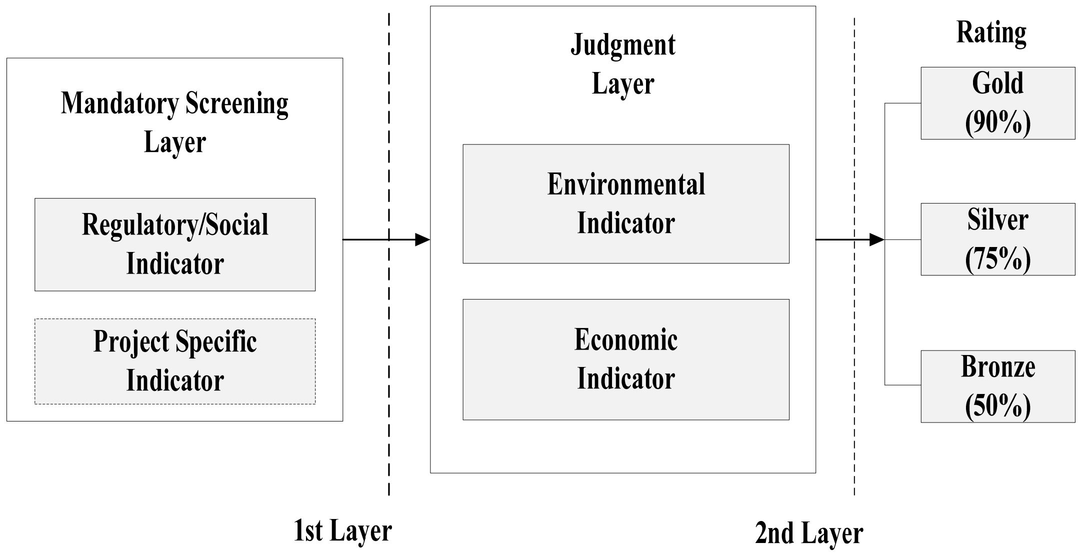


Figure 34
Schematic of BE2ST framework *[88]*

Sustainable Infrastructure Project Rating System (SIPRS)

To assess civil engineering projects in terms of sustainability, this program is not only created based on the technical performance of the engineering infrastructure, but also considers the "triple bottom line" of economic, social, and environmental impacts in sustainability measurements. In this rating system, the efficiency of an infrastructure is defined by the manner in which the infrastructure performs while interacting with other infrastructure components in its community *[4]*. This is based upon the performance based approach.

Uniquely, this rating system emphasizes a "pathway contribution," in addition to a performance contribution of the project, usually considered in the majority of rating systems. The long-term consequences of a project are determined by pathway contribution, which reveals whether or not the operator chose the correct type of project. According to the preliminary SIPRS System Manual, if the highway induces congestion or urban sprawl, it will receive a low rating, due to the pathway contribution standards *[4]*.

There are 10 main categories and 76 subcategories in the SIPRS system; the weight of each category is determined based on a survey distributed among various users and developers. Table 26 presents the different weights for the different categories.

Table 26

Weights of different categories in the SIPRS system *[4]*

Section	**# Subsections**	**Weight (%)**
Pathway	5	12.6
Project Strategy & Management	12	10.6
Community: Long & Short-Term Effects	10	10.7
Land Use & Restoration	12	8.9
Landscapes	3	7
Ecology & Biodiversity	7	8.8
Water Resources & Environment	6	11.5
Energy & Carbon	7	11.7
Resource Management Including Waste	8	8.2
Transportation	6	10
TOTAL	**76**	**100%**

Sustainable Transportation Environmental Engineering and Design (STEED)

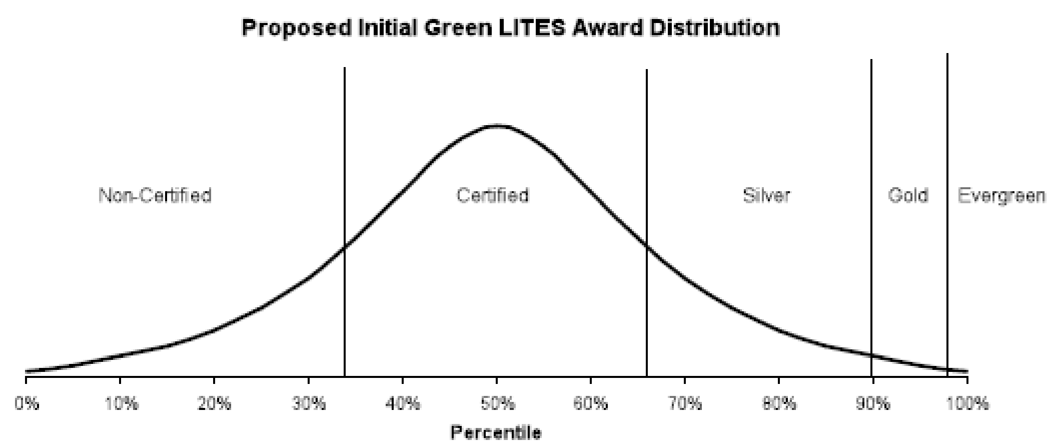
The Sustainable Transportation Environmental Engineering and Design (STEED) was developed by Lochner, Inc. and was presented by Gary Demich of Lochner, Inc. at the first green streets and highway conference. This approach applies the sustainability evaluation at the end of each phase of the project, to permit an easier understanding of which part of the project contributes to the project sustainability and which step degrades the rate of sustainability in the whole system *[4]*. This is a perspective qualitative approach as it has defined set of rules to be performed and rating are given based on the same; i.e., use of local materials, recycling, and reusing.

STEED results indicate that recycling and reusing materials leads to a more sustainable system. These two practices, on which STEED put more emphasis, will result in saving virgin materials. These methods suggest that the materials can be taken from the present site and reused in a future project. Furthermore, multiple usage of formwork would result in saving materials and money. In addition, by using a careful design in material dimension, accumulation of waste materials in the site would be reduced significantly, and thus result in energy and labor savings as well. Since the award levels may prevent a project from reaching the highest level of sustainable performance, no award levels were defined in this rating system *[4]*.

GreenLITES- New York State

Green Leadership in Transportation Environmental Sustainability, called GreenLITES, is a green highway rating system developed by the New York State Department of Transportation (NYDOT). Many different type of projects can be assessed through this tool. Although the GreenLITES project may cost slightly more than a custom pavement project, it has less social and environmental consequences. The GreenLITES approach concentrates on natural resource preservation, protecting the environment, improving project setting characteristics (historic, science, and artistic), utilizing smart growth, and other land-use programs *[89]*. NYDOT certifies the project that meets the requirements of the GreenLITES rating system. The project would be evaluated through the NYDOT process in the earliest stage (design stage). In this phase, a GreenLITES scorecard is filled out to measure the rate of sustainability in the design phase *[89]*. This is a perspective qualitative approach.

Scoring System. The GreenLITES certificate is granted to the projects at four different levels. These certification levels are determined, based on a comparison between the achieved score of the project and the available score levels in each stage *[89]*. These certification levels are presented in Figure 35.



Name	Point Range	Percentile Range	Approximate Std Dev Range	% of Dept Projects
Non-certified	0 – 14	< 33%	< -0.5σ	33%
Certified	15 – 29	33 – 67%	-0.5σ – 0.5σ	34%
Silver	30 – 44	67 – 90%	0.5σ – 1.5σ	23%
Gold	45 – 59	90 – 98%	1.5σ – 2.5σ	8%
Evergreen	60 & up	> 98%	> 2.5σ	2%

Figure 35
GreenLITES award description *[89]*

I-LAST – State of Illinois

The mutual efforts of the Illinois Department of Transportation (IDOT) and the engineering construction community resulted in the Illinois Livable and Sustainable Transportation Rating System and Guide, which is called I-LAST. The first version of I-LAST, released in 2009, was very similar to the GreenLITES approach. Yet, the I-LAST method was not a comprehensive approach to determine a sustainability rating. This is a performance-based approach, as it evaluates depending upon the quality at the end and compares with an available point, but it does not recommend following specific rules.

The intent of the I-LAST method was to create a vast library containing all available sustainable practices in highway construction, as well as the references and logic for utilizing the practices in pavement construction. To this end, IDOT focused on creating an effectual and user-friendly approach for monitoring highway projects based on the environmental aspects of pavement sustainability *[89].* In the scoring process, the desired project would be compared with the specified sustainability requirements. The project scores would then be presented as a fraction in a total of 219 available points in the project. If I-LAST is influenced by the user inputs, the method is not considered a mandatory approach for evaluating pavements in Illinois, and completely depends on the districts.

I-LAST Evaluation System. I-LAST utilizes a point scoring system analysis for evaluating pavement projects. Sustainability consideration involves a wide range of variables and boundary conditions, which differ in each individual pavement project. Therefore, the project's higher rating does not reflect a higher level of sustainability in regard to different types of practices. Being simple, understandable, and less time-consuming were the requirements of I-LAST *[90].* The evaluation system in I-LAST includes three general phases:

1. At the beginning of the project, the project team determines which elements are applicable to the project. Those items that are applicable can be noted and considered in the development of the project.

2. At the end of the design phase, the team determines which of the applicable items were included in the project plans. This evaluation can then be included in the project's file.

3. During construction, the contractor can utilize sustainable construction practices and techniques. The use of I-LAST can capture actual practices used by the contractor for the project. The contractor may also identify additional sustainable opportunities within the limits of the specifications *[90].*

A total of nine categories are considered in rating the pavement projects for sustainability: Planning, Design, Environmental, Water Quality, Transportation, Lighting, Materials, Innovation, and Construction. All have their own subcategories. Specific points are then assigned to the different practices in each subcategory *[90]*.

STARS – City of Portland (Oregon)

The Sustainable Transportation and Analysis Rating System (STARS) represents an integrated planning framework, developed by the North American Sustainable Transportation Council (STC). STARS provide planners, citizens, and decision-makers with a tool, which can assess the project in terms of sustainability *[91]*. The main difference between STARS and the other rating systems is that STARS developers believed that the majority of environmental impacts would appear during the use phase of the pavement. Developers could then recommend that the practitioners focus on "what to build" rather than "how to build" [*91*]. As it focuses on what to build rather than what to build, this is a performance-based qualitative approach.

STARS allow users to determine the goals and requirements of the projects, so that the STC could judge the most efficient procedure to reach the goals and objectives of the project. The STARS main objective was to combine the transportation and land-use strategies in a manner that satisfies residents and businesses for access to people and places, goods, services, and information. Using this approach, a solution for the neglected transportation problems in the traditional system would be attained *[91]*.

STARS-Plan

STARS-Plan is an innovative tool that provides the decision-makers with an integrated system that combines sustainability measures and transportation programs; such as Regional Transportation Plans and Transportation System Plans. The STAR-Plan provides users with a framework, which is based on performance meters that determine the way each individual plan satisfies its aims and objectives. The contribution of the STARS-Plan presents the ability of the program to simplify the decision-making process, based on outputs out of the short, medium, and long-term *[91]*. This is a performance-based tool.

The STARS-Plan consists of three phases. The objective of the first phase is to prepare the credit categories, goals, and objectives by means of continuous discussion. The second phase involves identification of the methods and metrics, which are required to satisfy the goals and objectives defined in the first phase. In addition, the focus of future stages of the STARS-Plan program would be on developing a low-capital/construction alternative, which concentrates more on operation stages *[91]*. The transportation personnel should be trained to utilize the STARS-Plan and also to create a rating system to evaluate pavement construction *[91]*.

The Center for Sustainable Transportation provided an explanation with respect to the characteristics of the STARS framework and the manner in which it works to meet sustainability requirements. The STARS framework attempts to satisfy the access needs of citizens and societies in a process that does not disturb the environment and human life. The framework is required to be efficient, reasonable, and to contribute to economic area growth. Further, the framework limits not only waste, but also GHG emission and reduces noise production, resource usage (non-renewable and renewable), and supports the recycle and reuse of materials *[92]*.

The Natural Step, proposed by Henrik Roberts and supported by the International Community of Scientists, consists of four conditions that preserve natural resources in order to sustain the human environment. The Natural Step's Four System Conditions states that a sustainable system does not influence the environment if the following objectives are achieved:

1. Extracting virgin substances from the earth interlayers;
2. Materials produced by human society;
3. Depreciation of the nature due to human activities;
4. The public does not ignore its needs because of the environmental conditions *[91]*.

STARS utilize "backcasting," proposed by The Natural Step. This planning method defines a future model at a very early stage, then determines the strategies and practices necessary to achieve the desired goal by a backward analysis *[91]*. Figure 36 illustrates this procedure.

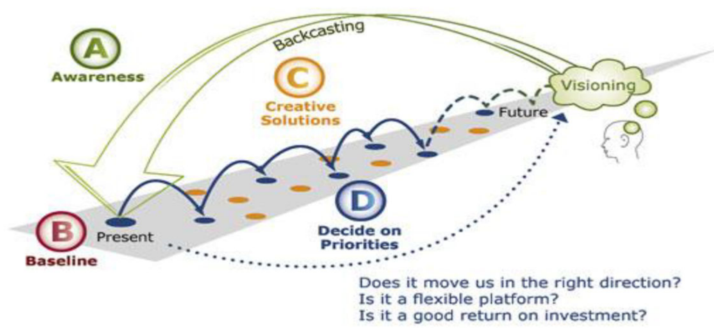


Figure 36
Backcasting procedure *[91]*

The Triple Bottom Line is one of the best frameworks to reach the sustainability defined in the Natural Step. Three categories in the Triple Bottom Line determine the consequences of a decision: People equity, environmental equity, economic prosperity. The STARS-Plan, designed as an explicit sustainability framework in which goals and objectives are built, is based on Triple Bottom Line categories. Figure 37 presents how the STARS-Plan interacts with the Triple Bottom Line in the process of determining goals and objectives *[91]*.

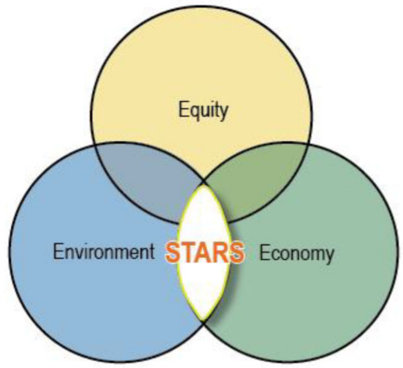


Figure 37
Triple bottom line in STARS-Plan *[91]*

Credit Categories. The STARS-Plans defines a total of seven categories in credit awarding, with one credit assigned to each category. These categories are: Integrated Process, Access and Mobility, Safety and Health, Economic Benefit, Cost Effectiveness, Climate Pollution and Energy Use, and Ecological Function. This method awards points, based on either achieving objectives or utilizing specific practices *[91]*.

The integrated process involves organizing the STARS-Plan, and consists of a list of essential elements. There are specific goals and measurable objectives determined for the rest of the credit areas. For instance, below the Access and Mobility credit, some goals and actions related to the Vehicle Miles Traveled and Multimodal Travel Reliability and Consistency are mentioned. Table 37 illustrates the credit categories and related elements or aims. When there is insufficient data to assess the objectives, the agencies would utilize alternative measures for the evaluation process *[91]*.

Table 27
Goals and activities according to each category *[90]*

Credit	Actions/Goals
Integrated Process	1. Acquire baseline data
	2. Create a Plan Stakeholder Committee
	3. Sustainability education
	4. Backcast plan goals and objectives
Access & Mobility	1. Improve access and mode choice
	2. Improve the convenience and predictability of trips
Safety & Health	1. Improve multimodal safety, especially for the most vulnerable users
	2. Improve health by increasing physical activity as part of transportation system
	3. Reduce exposure to airborne environmental

	contaminants
Social Equity	1. Reduce existing disparities in transportation investments
	2. Ensure that choice-constrained communities do not experience disproportionate impacts for transportation investments
Economic Benefit	1. Reduce fuel expenditures
	2. Increase economic resiliency
	3. Improve travel reliability and consistency for
Cost Effectiveness	1. Optimize benefits over life-cycle of the project
	2. Asset management and system adaption
Climate Pollution & Energy Use	1. Reduce greenhouse gas emissions and fossil fuel consumption
Ecological Function	1. Avoid habitat areas
	2. Reduce storm water pollution and hydrologic instability

Scale. The STARS-Plan is designed to utilize local Transportation Systems (TSPs), Regional Transportation Plans (RTPs), and modal plans such as a master plan for bicycles. This tool is not prepared to be used in decision-making programs developed at the state level such as STIPs (State Transportation Improvement Plans) *[91]*.

Timeframe. Since strategies may happen in an earlier than normal timeframe of transportation plans (RTP and TSPs), the STARS-Plan proposes that evaluation be accomplished within a six-year timeframe. In addition, the state plan is to mitigate Greenhouse gas emissions through the year 2050. The STARS-Plan requires practitioners to evaluate the strategies of Greenhouse gas mitigation based on a timeframe that extends until 2050. These different time periods that reflect the performance of the project are called "design years." Generally, the different "design years," suggested for planning, are summarized as follows:

- Short: Five or six years from plan adoption (some agencies use five-year planning horizons; some use six);
- Optional: ten or twelve years from plan adoption;
- Medium: 20 years from plan adoption;
- Long: by 2050 *[91]*

APPENDIX C

Sustainability Quantitative tools adopted by State DOTs

Best Economic Practices Adopted by State DOTs

According to DOTs, project funding is a major issue in pavement projects. With respect to budget limitations, it is very important to evaluate the type and dimension of the economic impacts for the whole project. Therefore, various types of cost analysis tools have been developed to achieve the most economic and sustainable pavements. A performance programming process by Montana State, investment scenarios by Oregon State, and a program menu and life-cycle cost analysis (LCCA) by Illinois are examples of methods applied to assess pavement economic impacts *[92]*.

Among the economic assessment programs, LCCA is widely applied by different DOTs. Most of these states developed a procedure based on each state's individual specifications, so that different tools were used in different states to evaluate the economic impacts of pavement projects. LCCA practices were reviewed by the following states: California, Colorado, Florida, Georgia, Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Oregon, Pennsylvania, Texas, Utah, Virginia, Washington, and Wisconsin.

The Michigan Department of Transportation (MDOT) uses AASTHO's DARWin program. Three states developed a custom software package for performing LCCA. In this category, Georgia, Minnesota, and Pennsylvania DOTs use a custom spreadsheet for performing LCCA. The analysis period is assumed to be 40-50 years in most states. Almost 50% of the states use a discount rate of 4%. States such as Colorado, Michigan, Minnesota, and Washington use rate-based recommendations from the Federal Office of Management and Budget *[93].* While FHWA recommends the use of LCCA, the following states do not include user costs in LCCA: Illinois, Minnesota, New York, Ohio, Virginia, and Wisconsin.

Each state has its own practices in performing LCCA, the LCCA tool used, the analysis period, the discount rate, and inclusion of user costs. States such as California, Colorado, Florida, Indiana, and Washington use RealCost software. It should be noted that the selection of the discount rate is critical. A high discount rate will be positively biased towards projects with a low initial construction and a higher maintenance cost, while a low discount rate will be positively biased towards projects with a high initial cost and a low maintenance cost *[93]*. As per NCHRP 703 report the historic discount rate ranges from 4%. The selection of discount rate is based upon the long-term real discount rate values provided in the latest edition of the Office of Management and Budget (OMB) Circular Appendix C, which is updated yearly. Even with the selection of the discount rate from the recent OMB, Appendix C is prone to change. The use of discount rate varies depending upon the historic discount factor and therefore, a contractor proposes a triangular distribution factor with variation up to the factor of 0.85 to 1.40 with the actual discount rate *[94]*. Apart from the discount rate, the level of detail in LCCA depends upon the level of investment. The level of detail goes on increasing as the investment increases from insignificant to minor to major investments.

The definition of user costs varies from one state to the other. In California, user costs and agency costs are considered to have the same value. In Florida, the user cost includes motorist delay time, accidents cost, and vehicle operating cost. In Georgia, user costs and agency costs are calculated separately and are assumed different, with that difference preventing them from being added together. As a result, the user cost value is evaluated separately in a decision-making matrix to evaluate the separate importance. There are also states that consider user costs and states that do not. States such as California, Colorado, Indiana, Michigan, Pennsylvania, Texas, Utah, and Washington consider user costs in the calculations. However, states such as Illinois, Minnesota, New York, Ohio, and Virginia do not consider them. States such as Florida considers the inclusion of user costs as optional. Yet, states such as Georgia consider user costs to be a factor in a weighted average *[93]*.

Each state performs its LCCA based on specific requirements. For example, in Colorado, LCCA is performed for a comparison of concrete pavement to asphalt pavement for either new or reconstructed projects with an initial value of $2 million or more. Also, the comparison pertains to asphalt and concrete surface treatments with an initial value of more than $2 million, an instance where both pavement alternatives are considered feasible. It should also be noted that Colorado incorporates statistical research and experience from a current project for integration in long-term plans *[95]*.

Illinois performs LCCA for both new and reconstructed pavements with more than 4,750 square yards of pavement and/or pavement costing more than $500,000. In the event that the economic analysis for one option is no greater than 10% cheaper than other options, the pavement selection process will be based on alternate bidding. In Indiana, an LCCA is performed when there is more than one alternative. It is also performed for new and rehabilitated pavements with a mainline pavement of more than $10,000 per square yard. In the event that two scenarios are evaluated, and the net present value is within 10%, those alternatives are considered to be the same. In this case, factors, such as initial costs, constructability, work zones, and user costs, are used to make the final decision. User costs are inclusive of user delay cost during construction, vehicle operating and accident expenses, fees and other costs during the life cycle. Indiana also requires changing the pavement design life to test LCCA sensitivity, based on current pavement conditions. This also applies to New York, where sensitivity analysis is performed to evaluate the sensitivity of LCCA for a particular variable.

In Ohio, an LCCA is performed when more than one feasible alternative exists. In case the life-cycle costs for more than one alternative are within 10% of the lowest life-cycle cost alternative, the alternatives are considered to be equal to the lowest alternative. Any of these equal alternatives can be selected. However, when alternatives are not within 10% of the lowest alternative, these options are eliminated. In case there are no alternatives within 10%, the lowest cost is selected automatically. In the event alternatives are not within 10% of the life-cycle cost of the lowest pavement, then the lowest cost alternative is selected.

Minnesota considers the remaining life for the pavement. The remaining life is defined as the "prorated" share of the cost of the latest activity, based on the service life extending after the analysis period. The state of Oregon performs LCCA in case of constructing new pavement of more than one mile, or in the case of major pavement rehabilitation involving total reconstruction or rehabilitation. Also, an LCCA is performed when pavement design strategies are less than a minimum value of 15 years.

Pennsylvania performs LCCA for all structural improvements with a value exceeding $3 million for total projects costs on the interstate and $15 million for all other facilities. In a comparison of two alternatives, the alternatives should have the same analysis period. Additionally, the LCCA is performed without a separate inflation rate. When there is a difference of 10%, this becomes sufficient to determine the type of pavement. It should also be noted that Pennsylvania used historical data to develop the LCCA inputs. In a positive view, Pennsylvania worked with the industry in developing this approach, which increased transparency.

Texas applies two different software for performing an LCCA, the rigid pavement life-cycle cost analysis (RPLCCA) and the Texas pavement type selection (TxPTS). The RPLCCA is used to evaluate various pavement designs, together with all the associated costs over the pavement life, and then ranks them according to cost. A performance assessment model is included in RPLCCA, which evaluates the distress rate for each pavement type. However, RPLCCA requires a large number of inputs, including factors difficult to determine, such as emissions, accident, vehicle operating costs, etc. TxPTS is a tool that allows the comparison of several pavement strategies, then ranks them according to cost. TxPTS is similar to RPLCCA, except that TxPTS needs fewer user inputs, which allows for an easier use. Also, TxPTS does not calculate distresses. However, TxPTS includes flexible pavements, while RPLCCA only considers overlays.

Utah uses two manuals for conducting LCCA. These manuals are Pavement Management, and Pavement Design Manual and LCCA. Utah DOT does not consider salvage value or energy costs when evaluating LCCA. Factors that are included are funds availability, project specific information such as environmental conditions, and project specific information. The user costs are evaluated by the regional pavement engineer.

Virginia DOT applies the present worth method in LCCA. However, when the design life is not the same, the EUAC method is used. When the performed LCCA results are within 10%, other factors are considered. In Washington, the user cost considered is associated with user delay, linked to traffic volumes, construction periods, etc. When one of the alternatives is found to be 15% greater than the other, the least expensive one is selected. However, when an alternative is within 15% of the other alternative, the state DOT performs an engineering analysis. In Wisconsin, pavement type selection is based on the outcome of LCCA. The lowest cost alternative is selected. When a 5% difference between the desired design and the lowest price one is found, then more documentation is required for a final decision *[93]*.

LCA Adopted by Different States

Current Road condition of US roadway network is rated as D, which represent that most highway is in deteriorating condition. Rehabilitation is needed in majority of the US road network. This indicates towards the huge amount of economic resources as well as such extensive construction will lead to the more environmental burden. So, state and highway agencies are trying to enforce sustainability during the roadway network development and rehabilitation. For the same a good estimation on life-cycle costs and environmental impacts is one of the integral step in the highway investment decision-making process. Apart from LCCA, Life-cycle assessment is currently used by different state and agencies to evaluate the energy consumption, emissions generation and natural resources consumption.

The California Department of Transportation has conducted a pilot study (Caltrans) for better understanding of transportation planning, economic analysis and managing the risk of decisions regarding freight. In this study, the road conditions of two different sections were analyzed to determine the current road conditions and predict the potential future condition and the subsequent environmental and economic effects. As road conditions, mainly roughness, have direct impact on the energy consumption and emissions, by knowing the future condition of the road, a reliable environmental impact can be predicted. Potential freight damage relationship was established based upon the existing vehicle operating cost (VOC) and environmental models. Pavement surface profiles on the Interstate and state Highway system (SHS) was developed by the accelerations of trucks, trailers and their freight. Similarly, principles of Pavement Vehicle Interaction (V-PI) and state-of-the-art tools were used to simulate and measure loads. The study showed a valid result and can be applied widely. From the tire loads on a different route, different level of roughness can be determined, and the same can be used in the road pavement design and the subsequent environmental impact. Effects of different levels of quality in construction/ maintenance was used to evaluate road roughness which directly links the expected life and user costs. Further, the level of roughness on different routes can be used as an input into different economic models and benefit/cost ratio can be obtained. This gives the users the option to select the design alternatives when the same is used to predict the future condition of the roads as the maintenance and rehabilitation works. The model was used to predict the optimum riding quality for minimum vehicle operation costs (VOC). The VOCs can be used by the private sector companies to calculate the costs of travelling on a specific route, and provide an economical road, which may cover a longer distance but with a lesser cost due to the low roughness value. Roughness also helps in route planning as by adopting the smoother roads *[96]*. Apart from these, the pilot study has provided some indications of potential considerations for pavement LCA which reflect decisions and actions by the roadway infrastructure owner/operator and its roadway users. Relationship between environmental, economic and road conditions will help in understanding and evaluating for the maintenance and rehabilitation phase of a specific pavement and helps in decision making for the selection of roads that is economically feasible and has the least environmental impact *[96]*.

The Illinois tollway program provides a safe and reliable highway network for its occupants. To maintain the safety and reliability of the highway network, it has been monitoring and documenting sustainability in the Tollway network. Apart from documenting the current sustainability of the tollway program, historical information has been recorded to address and improve pavement sustainability. The historical era included Congestion Relief Program. These programs will be compared to each other, and all of them will be compared to a baseline level of sustainability from the late 1990's, referred to as Tollway 2000 *[97]*.

Illinois has chosen two approaches for addressing and monitoring sustainability of their transportation network. One being the qualitative approach INVEST V1.0 and other being the quantitative approach, LCA. LCA has been used to evaluate the environmental impact due to the energy consumption and emissions due to the different activity on the tollway. A certain energy is required for the function of the tollway and requires certain material inputs and requires fuel which result into different forms of emission. So, to quantify these impacts properly, the Tollway is developing an open-source, spreadsheet-based, LCA tool. These tools allow project designers and tollway contractors to modify materials, equipment, and procedures to reduce the amount of energy consumed and by extension, the amount of greenhouse gases released into the atmosphere. Pavement is one of the five areas of tollway for which the energy emissions will be calculated *[97]*. A public commitment has been made by the tollway to build the "greenest" program which is known as Move Illinois. LCA has been widely used to push innovations to make it greener. LCA has been used in the decision making for the construction, operation and use of the highway. Further LCA, has provided the motivation for green road construction and allows the tollway to understand which green initiatives give the “best bang for the buck.” Finally, LCA is proposed to be applied to establish reasonable sustainability goals for all projects. Apart from the selection of alternatives, it is supposed to provide incentives to contractors to achieve sustainability during material selection, construction and equipment selection *[97]*.

A study was conducted to examine the LCCA practice used by the Colorado Department of Transportation (CDOT) and proposed a regional LCA model to determine the greenhouse gas (GHG) emissions associated with Colorado highway pavements. LCCA and LCA was conducted on a Portland cement concrete pavement (PCCP) and hot-mixed asphalt (HMA) alternatives, for a highway rehabilitation project *[98]*. In context of LCCA the difference between the two accounted for only 7.4%. But in context of the LCA, the GHG emission from HMA was more than PCCP (PCCP emissions was 26% less than the HMA) over the 40-year analysis period. CDOT has been using LCCA tool for the decision making in alternative selection. This studied wasn’t conducted by the CDOT and hence doesn’t signifies the LCA practice by the state DOT. It provides a recommendation that the LCA can be an optional criterion for the selection of the preliminary pavement type *[98]*.

The Washington State Transportation Center (TRAC) performed a comparative LCA between the three different replacement options for aged Portland Cement Concrete. The main objective of this study was to summarize the impacts from different alternatives to give recommendations for the “greener” roads in Washington State *[21]*. Replacement with a new PCC pavement, removing and replacing with hot mix asphalt (HMA) pavement, and cracking, seating and overlaying (CSOL) the existing pavement with HMA were three alternatives that were compared for the life span of 50 year on a I-5 section, which was in end of usable life use. Six different categories namely Global warming potential, Acidification potential, eutrophication potential, Human heath criteria air pollutants, energy usage & photochemical smog were used in the study *[21]*. However, due to data source limitations and study scope only air emissions and energy usage were used to quantify the environmental impacts of different pavement replacement and rehabilitation strategies. The assumptions made on this study was that all the three alternatives would be acceptable for final pavement to be higher than the original pavement. But if this was not acceptable, this scenario could change the conclusion of LCA and should be addressed in the inventory for the better prediction of the result. Pavement preservation for a life span of 50 years and additional preservation at the end of life was scheduled. However, the pavement neither had a well-defined end of life nor its recycling benefit was stated. Therefore, the pavement was not truly analyzed from cradle to grave. After applying normalization, the PCC removal and replace option for one lane mile uses 3,840,000,000 BTU or almost 12 times the energy as a person uses in a year. An HMA remove and replace project for one lane-mile uses more than 18 times the energy as one person uses in a year. A one lane-mile CSOL project uses a little over 10 times the energy as a person uses in a year (in 2004 average energy consumption per person was 323.1 million BTU) *[99]*. So, it can be concluded that CSOL has least environmental impact. As the existing pavement was not removed and the least paving material was required. Also, it requires least labor and materials too due to existing pavement and is the least expensive one. The main assumption on this research was that the structural integrity for CSOL was same as other two. But Washington has not much experience on CSOL. So, this study recommends WDOT or other agency to investigate on the validity of CSOL as a Long pavement. For global warming potential and human health criteria air pollutants the PCC replacement option was a greater contributor and for the remaining categories the HMA replacement option was the largest contributor. This can be verified by the PCC's larger contribution to CO_2 and particulate emissions and by HMA's larger contribution to nitrogen and sulfur oxides *[21]*. The reuse/recycling of the remaining materials, at the end of their service life of each pavement type, presents a concern as to which one would be more beneficial if used in the new pavement project. However, the largest contributor to different impacts was primarily due to the production of materials in all the alternatives. So, this recommends WDOT and other agencies to research more on reducing the impact due to the production and manufacturing of pavement materials, whereas the recycling of the removed materials becomes a second option *[21]*.

The Texas Department of transportation (TxDOT) has adopted three construction activities to reduce the GHG emissions due to the Asphalt pavement *[100]*. Use of RAP, RAS and warm mix asphalt (WMA) not only reduces the CO_2 emission reduction, it benefits the material conservation, reduces energy consumption and saves money associated with the production cost of asphalt and aggregates. Use of RAP and WMA has been development and implemented in the Texas road networks and has proved to be a good sustainable practice. But the use of RAS in TxDOT is new alternative for construction and is in developing stage. RAP has been mostly used in state road network in comparison to the other two and it is predicted that the scenario will be the same in future. Figure 38 below shows the effect of these technologies on CO_2eq emissions. Figure 38 shows that the CO_2eq emission has been reduced and predicted that the trend to be continued in future as well. But, due to the technical constraints, the use of RAP and RAS may be limited and will allow more use of WMA, which would drastically reduce the emissions. The proportion that resulted in the beast case scenario with least CO_2eq was when 90% of WMA, 20% of RAP & 2% of RAS is utilized *[100]*. The amount of reduction is CO_2eq can be converted into equivalent savings for commonly used consumer identifiable items. As, these technologies has significantly contributed in the reduction of CO_2eq emissions, TxDOT has allowed the use of these in its specifications and its implementations is continued at an increasing rate. TxDOT recommends that the use of these technologies should be expanded and should provide additional benefits to the citizens of the state. These technologies should be clearly understood by the highway agencies DOT and contracting community to work together and extract the full benefits from these innovative technologies. Texas transportation Institute also recommends more research on these methodologies to illustrate the energy of construction, material conservation, greenhouse gas, air pollutant emission reductions and cost savings. Further it recommends to account for the savings associated with the entire life cycle of the pavement rather than the benefits associated with only the initial use of these technologies *[100]*.

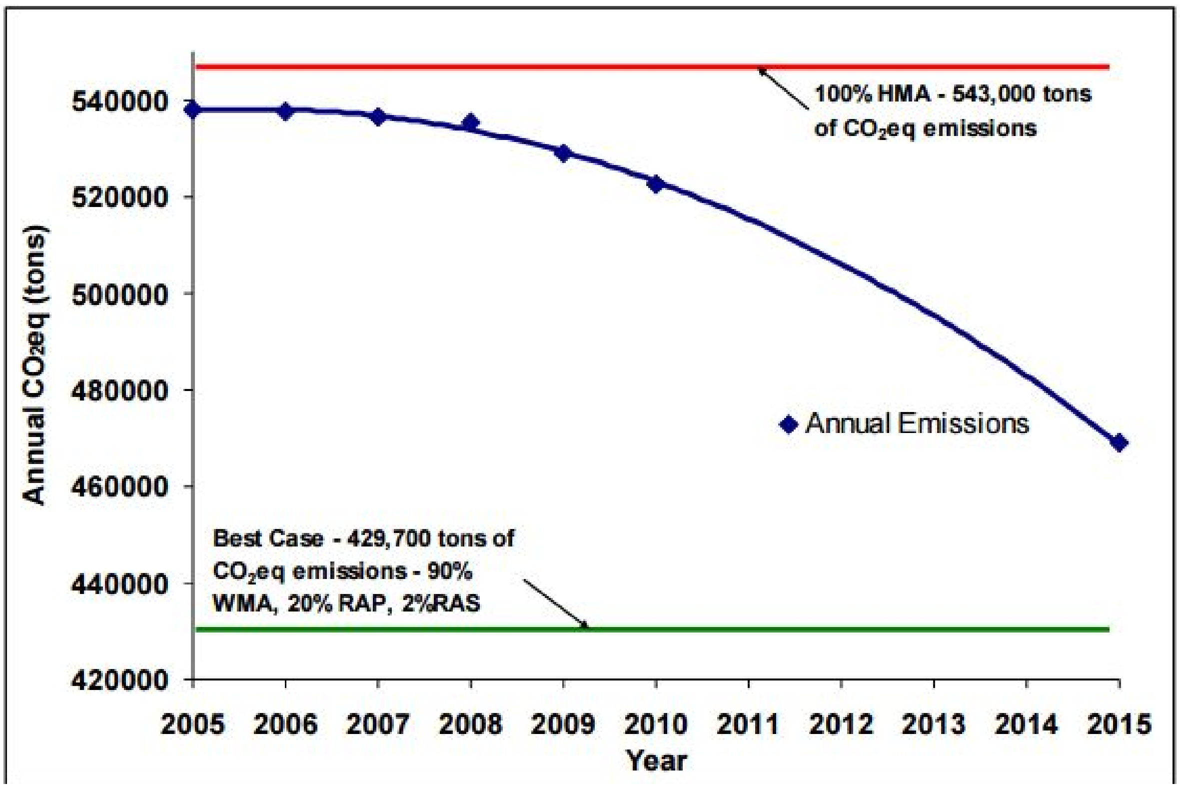


Figure 38
Effect of technologies on annual CO_2eq emissions *[100]*

APPENDIX D

Review of Past Studies in Pavement LCA

This section reviews some of the noteworthy research studies in LCA application to pavements. The goal of this review is to evaluate the depth and benefits of the conducted research studies through each stage of LCA. This type of review would be helpful in recognizing the knowledge gaps among the different methodologies.

Generally, the focus of life-cycle assessment analysis is to determine the environmental impacts associated with the life-cycle phases, based on predefined impact categories. Although a comprehensive assessment of the life-cycle is the ultimate goal of all LCA studies, time and resource limitations encouraged researchers to reduce the complexity of the scope in order to evaluate only the most important processes. Therefore, some of these studies included the life-cycle inventory and did not conduct an impact analysis. Table 28 represents a summary of LCA studies that will be discussed in the following sections.

Häkkinen and Mäkelä (1996)
This study was one of the most comprehensive studies, covering the entire phases of pavement life-cycle, except for the end-of-life stage. The study made a comparison between a Stone-Mastic Asphalt (SMA) and a doweled Jointed Plain Concrete Pavement (JPCP). Eighteen different environmental categories were selected to analyze these two different pavement types. CO_2 emissions, energy consumption, air pollutants, and heavy metal releases were among these categories. The evaluation was conducted on a kilometer of pavement known as the Tampere Motorway in Finland. The amount of daily traffic in this section of road was 20,000 vehicles *[101]*.

The environmental weights of the material phase were determined for both pavement types based on the quantification of the upstream supply chain of each component. Factors such as "studded tires" and "road salting" were also considered in the design, maintenance, and use phases.

In this study, the "fuel consumption" factor, as related to paving equipment, was the only construction factor that was considered in the LCA framework. While traffic delays were neglected, due to a utilization of new pavement construction methods, the traffic disturbance caused by maintenance and rehabilitation processes was considered as well. A time period of 50 years was selected for the maintenance and rehabilitation phases. These plans included one or two grindings for the concrete pavement, as well as milling and overlays using recycled and virgin materials for the asphalt pavement *[101]*.

The authors also considered the use phase in the LCA analysis. According to the scope of the study, fuel consumption, noise, lighting, dust, and concrete carbonation were the impact categories considered in the analysis. Furthermore, the researchers conducted a vehicle traffic analysis, which considered an AADT equal to 20,000, to simulate the environmental impacts associated with fuel consumption. The amount of emissions caused by the 50 years of service was approximately two times more than the total emission through the remainder of the life-cycle stages of the pavement. In addition, through the "what if" analysis, it was concluded that should the fuel consumption decreases in a range of 0.1 to 0.5% due to a change in the pavement characteristics, the vehicle emission reduction would remain similar to the amount of emission throughout the entire life-cycle of the pavement *[101]*.

Results showed that the rate of producing emissions for CO_2, NO_x, CO and mercury (Hg) in concrete pavement was 40 to 60% higher than for the asphalt pavement during production of materials, construction, paving, maintenance, lighting and traffic disturbance. However, on the other hand, when the energy consumed through the processing of asphalt is considered, the non-renewable energy consumed by asphalt pavement was approximately two times higher than for concrete pavement. Results also showed that there exists a balance in the rest of the environmental impact categories between the two pavement types.

Mroueh et al. (2000)

This study focused on an evaluation of industrial by-products in pavement construction projects. One kilometer of pavement road in Finland was selected as the case study and an AADT equal to 7,000 was assumed along with a percentage of heavy trucks of 14% *[102]*. Through the potential applications of coal ash, crushed concrete waste, and blast furnace slag as virgin materials substitutes for seven pavement structures, the environmental impacts of each pavement was evaluated by means of the LCA framework. The research study considered the most significant environmental impacts, which included raw materials and secondary products consumption, usage of fuel and other energy, emissions of carbon dioxide, nitrogen oxides, sulphur dioxide, VOC, carbon monoxide and particles, infiltration of different compounds into underground sources, and noise. These impact categories were applied to the materials, construction, and maintenance stages of the pavement life-cycle. However, this study did not examine the use phase and end-of-life stage *[102]*.

Table 28
Summary of the LCA studies *[33, 101, 102, and 103]*

Research (year)	LCA approach (system boundary)	Analysis period (years)	Functional unit	Traffic	Outputs
Häkkinen and Mäkelä (1996)	Process (materials, construction, use, M&R)	50	1 km	20,000 AADT	Emissions (CO_2, SO_2, NO_X, CO, HC VOC, heavy metals, particulate, problem wastes, N into water, COD), energy (fossil fuel, electricity inherent energy), dust, use, salt, noise, lighting land
Mroueh et al. 2000	Process (materials, construction, M&R)	50	1 km of highway in Finland with 7,000 AADT and 14% heavy vehicles	7,000 AADT, 14% Truck	land use, Effluents to soils (leaching metals, leaching or migration of organic compounds from materials, Cl, CO4), emissions to air (CO2, NOx, SO2, VOC, CO, particles), wastes (inert waste), noise
Zapata and Gambatese (2005)	Process materials, construction	~10	1 km	~10 × 10^6 ESAL	Energy
Chan 2007	Process (materials, construction, M&R)	undefined	1 km section	Variable	Energy, air emissions (CO2, CH4, N2O, Pb, VOC, NOx, SO2, CO, PM10)

In the materials production stage, a method of data processing was assumed, similar to that of Häkkinen and Mäkelä (1996). In the construction phase, the authors did not specify the equipment, choosing to focus on the relative emission factors used in the analysis. The data presented were limited to a bar chart that indicated the total energy consumption in the construction activities. The design of the maintenance phase was based on the Finnish strategy, implemented by Häkkinen and Mäkelä *[101]*. In this study, the maintenance phase was considered to be the same for asphalt and concrete pavements, and thus insinuated that performance curve patterns were identical for both. This assumption raises some concerns about the accuracy. Results of the analysis illustrate that while the energy consumption in the maintenance phase could be considered critical, other impacts, such as CO_2 emission, tended to be minimal.

This study produced an aggregated score of different environmental impacts based on an expert assessment system. In this method, a final score is obtained by summing up the different environmental weights. The weighting system was designed in a way that the weight of the materials and energy consuming categories would be higher than the weight of the other categories, such as water consumption and noise production. Generally, when a recycled material is used in the pavement construction process, it would result in a more sustainable pavement construction, in comparison with to the application of virgin materials *[102]*.

Chan (2007)

The author reviewed 13 DOT projects in Michigan. This study pursued two main objectives. First, the review attempted to determine the limitations of life-cycle cost analysis (LCCA), and second, the study explored methods to incorporate the pollution effects in the LCCA framework. The study also conducted a comparative analysis between asphalt and concrete pavements. The type of projects analyzed in this study involved newly constructed, reconstructed, and rehabilitated ones. The environmental categories considered in this study included resource usage, greenhouse gas (GHG) emissions, typical air pollutants and hazardous materials *[33]*.

The environmental data drawn from mix design information such as the Portland Cement Association (PCA), the Athena Sustainable Materials Institute, the IVL Swedish Environmental Research Institute, and SimaPro 6.0, were used to compare the environmental impacts of different surface materials used in pavement construction. The "EPA NONROAD 2005 model," created by the EPA for modeling diesel engine emissions, quantified the rate of emissions caused by vehicles and construction equipment during the construction stage. In addition, the environmental impacts caused by upstream activities, as related to fuel production, was specified on the basis of SimaPro 6.0 data *[33]*. A consideration of traffic delays due to construction activities presents the most significant contribution of this study to LCA research. The amounts of energy consumption and CO_2 emission in the construction phase were similar to the material production stage [*33]*.

Generally, the results of this study confirmed the previous attempts in terms of comparing the energy consumption for asphalt and concrete pavements. This report concluded that the energy consumed in asphalt pavement construction was more than for concrete pavement if the energy of processing asphalt binder is considered, as the nonrenewable energy consumption for asphalt is significantly higher than the concrete. Otherwise, there would be no significant difference between the two types of pavements. In addition, this study integrated both LCA (life-cycle assessment) and LCCA (life-cycle cost analysis) in the analysis.

Zapata and Gambatese (2005)

A comparison between a continuously reinforced concrete pavement (CRCP) and an asphalt pavement was conducted in terms of energy consumption. Construction and material stages were evaluated through the life-cycle of both alternatives. Before conducting this research, different researchers reported conflicting results concerning the amount of energy consumed by CRCP and asphalt pavement. The results presented by Horvath and Hendrickson (1998) contradicted those reported by Stripple in 2001 *[103]*. After applying the same boundary conditions for their research, Zapata and Gambatese found that the use of two different LCA approaches was the reason for this contradiction. Input and Output (IO) LCA and process-based LCA are two different approaches that caused the difference in results. In this study, the process-based LCA was selected as the LCA analysis method of choice *[103]*.

Results of the study identified materials production and construction stages as the most energy consuming phases in the life-cycle of CRCP pavement. The conclusion was that the production of cement proved to be much more energy consuming than the process of producing asphalt binder. Furthermore, the study found that in asphalt pavement, drying and mixing the aggregates is the dominant processes in terms of energy consumption. On the other hand, the amount of energy consumption in CRCP was governed by cement production. The authors concluded that consideration of the feedstock energy of asphalt binder plays a significant role in the determination of energy consumption, thereby causing a large difference between the two types of pavement in terms of energy consumption.

APPENDIX E

Methods to Improve Pavement Sustainability

Methods to Improve Sustainability in Asphalt Pavement Construction

In this section, recommendations for construction of the subgrade, subbase, base, and asphalt layers are presented:

- The level of compaction in granular layers must satisfy the target density. The other construction activities are excavation, leveling, hauling of excavated or borrow materials. In addition, construction should use available crushed aggregates around the site whenever possible.

- There are several steps that should be completed in order to produce an asphalt mixture layer such as AC preparation, transportation, material lay-down, and compaction. The fuel consumptions associated with each construction step are presented in Figure 39.

Surface HMA Course
Binder HMA Course
Base Course
Compacted Subgrade
Natural Subgrade

Construction Activity	Fuel Factor
Subgrade Preparation (grading and finishing)	0.300-0.700 gals/cubic yard
Base Layer Preparation (hauling, placement, and compaction)	0.400-0.600 gals/ton
Asphalt Mix Production (diesel)	1.500-2.000 gals/ton
Asphalt Mix Hauling (>15 miles)	0.514 gals/ton
Asphalt Mix Placement	0.273 gals/ton

Figure 39
Paving equipment and the fuel factors *[4]*

The approximate level of energy consumption, as well as GHG production for different types of construction equipment utilized in asphalt pavement construction are provided in Table 29.

Table 29
Approximation of energy consumption and GHG production of paving tools *[4]*

Construction Activity	Equipment	Horsepower Range	Fuel Consumption Range (gal/hr.)	CO_2 Emissions Range (lb./hr.)
Asphalt Paving	Paver	125-225	35-50	90-136
	Pneumatic Roller	100-135	6-12	45-136
	Vibratory Roller	100-135	4-6	226-1130
Milling	Milling Machine	400-875	2-6	113-339
Excavation and Placing	Excavator	100-320	10-50	136-226
	Vibratory soil compactor	100-180	5-15	271-361
	Bulldozer	250-500	6-10	90-136

Several practices may be used to enhance sustainability during asphalt pavement construction activities. In order to assess the effectiveness of these practices, a comprehensive LCA method should be applied through this phase. Table 30 presents some of these sustainability improvement practices. The following sections discuss specific strategies that help mitigate the related environmental impacts *[4]*.

Table 30
Summary of sustainability practices during asphalt pavement construction *[4]*

Objectives	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Achieve Target Density Requirements	Increase thickness to nominal maximum aggregate size ratio	Potentially reduce costs since it can reduce number of lifts constructed	Reduce environmental impact through less hauling trips Increased pavement life due to better compaction Better resistance to top-down cracking	Longer life and less frequent interventions
	Use warm-mix technologies	Potentially increase costs due to additives and capital investment	Reduce environmental impact by lowering compaction temperature	Reduce construction related air pollution and potential for irritation for sensitive workers
	Follow laydown temperature requirements	No change in cost	Accelerate construction due to achieving required mat thickness and density at a faster rate	Less exposure to traffic delays
	Select proper equipment for placement and compaction equipped with smart technology	Need capital investment and increased agency costs but has long-term benefits to contractors and agencies	Reduce environmental impact through good quality materials and longer life pavements	Longer pavement life Less intervention
Prevent Segregation	Use thermal cameras to avoid erratic mat temperatures and temperature related segregation	May increase contract costs due to capital investment	Reduce environmental impact through good quality materials and longer life pavements	No direct impact
	Use of material transfer vehicles	May increase contract costs	Reduce environmental impact through good quality materials and longer life pavements	Longer pavement life Less intervention

	Proper handling of materials during transportation, placement, compaction	No cost associated with this approach	Reduce environmental impact through good quality materials and longer life pavements	Longer pavement life Less intervention
Construct Effective Longitudinal Joints	Avoid segregation during transportation and placement	No cost associated with this approach	Reduce environmental impact through good quality materials and longer life pavements	Improve ride quality Longer pavement life Less intervention
	Use of adhesives or sealants overbanding the joint	May increase contract costs	Reduce environmental impact through good quality materials and longer life pavements	Improve ride quality Longer pavement life Less intervention
	Proper compaction to achieve joint density	No cost associated with this approach	Reduce environmental impact through good quality materials and longer life pavements	Improved ride quality Longer pavement life Less intervention
Achieve Target Smoothness Requirements	Proper placement and compaction techniques	No cost associated with this approach	Reduce environmental impact through reduced fuel consumption	Improve ride quality Longer pavement life Less intervention

Asphalt Layer Placement and Compaction. With the large amount of asphalt pavement in the United States (about 500 million tons yearly) and the prevalent usage of asphalt mixes, even a small enhancement in the construction process would result in a significant improvement in construction sustainability. In addition, there are applicable practices to prevent hazardous asphalt fume emissions and to reduce the possibility of being exposed to dangerous emissions related to asphalt paving construction. Some of these practices are presented in Table 31.

Proper construction of the underlying layers (subgrade, subbase, and base) through adequate compaction, together with asphalt mix placement, can ensure foundation quality and long-term performance. This would also avoid segregation and longitudinal joint deterioration, and help in achieving the desired density, grade and cross slope, and smoothness. Several suggestions and guidelines regarding asphalt concrete compaction methods and effective placement practices are presented in the following section.

Strategies to Control Segregation. Inappropriate mixing of asphalt concrete may result in segregation, which may occur during different construction stages, such as placement process, transportation, or production. During the production stage, segregation can be controlled by considering items such as mix design modification, adjusting incorrect material proportioning from the stockpiles to the bins and from the bins to mixers, and enhancing managing and pumping of mixtures in the storage. Monitoring the paver hopper and auger during the paving process can also be beneficial for control of the segregation. In addition, the segregation can be kept at a minimum level by utilizing a Material Transfer Vehicle (MTV) given its ability in remixing the asphalt mix and maintaining the whole mixture temperature at the same level *[4]*.

Table 31
Practices to mitigate harmful asphalt-related emissions *[4]*

Location	Best Practices
Plant	Select plant mixing temperature by consulting asphalt supplier
Plant	Read the material data safety sheet for all materials
Plant	Regularly calibrate thermocouples
Plant	Collect continuous data on aggregate moisture and fuel/energy usage
Plant	Have stack gases tested to check limits
Plant	Keep a record of fuel usage over time
Plant	Do not use diesel fuel and kerosene as release agents
Paving Site	Keep paving temperatures as low as possible (blue smoke indicates overheating) consistent with achieving adequate compaction of the mat
Paving Site	Check paver ventilations systems regularly
Paving Site	Ensure that tail pipe and ventilation stacks exhaust above the height of the paver operator
Paving Site	Consider increasing mat thickness prior to an increase in plant temperature

Build a Quality Longitudinal Joint. If the longitudinal joints do not meet the requirements, the service life of the pavement and quality of driving would be reduced accordingly. Several reasons may cause longitudinal joint deficiencies such as low density, segregation, and lack of adhesion between two neighboring lanes. The lowest density of a longitudinal joint should not be more than 2% less than the mat density and with no density measurement being less than 90% of the theoretical maximum density. If the lift thickness is in the range of 1.5 to 3 in., a notched wedge joint can be used. The other alternative is to utilize joint adhesives or to tack the joint face with asphalt binder. These recommendations can be helpful to reduce joint density problems.

Meet the Density Requirements. Achieving a smooth surface and required level of density are the most significant goals of the compaction process. At the minimum level, the density should be 92 to 93% of the maximum theoretical density. According to the literature, a strong relation exists between the pavement service life and the density of the asphalt layers. Figure 40 presents the effects of density improvement on pavement service life. An appropriate level of density can also reduce pavement vulnerability to both rutting and cracking.

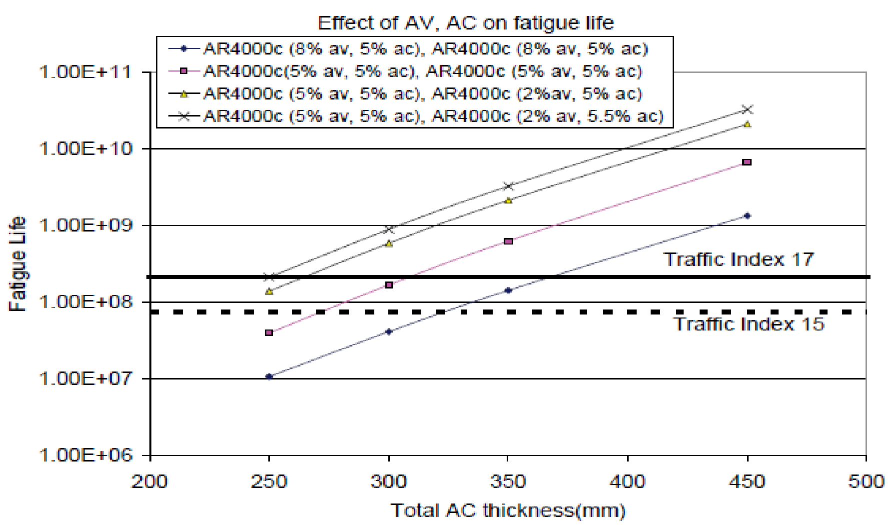


Figure 40
Relationship between density improvement and pavement service life *[4]*

To achieve an adequate compaction process, more attention should be given to specifics, temperature checking, and supervision of the factors that influence the quality of the compaction. Generally, improving mat density can enhance the crack and rutting resistance of the pavement. The factors that affect the quality of compaction in asphalt pavement can be classified into the following categories:

- Mix specifications, such as aggregate, binder and polymer type, and mix design;
- Environmental conditions – Generally, asphalt placement is not allowed in rainy days and air temperature should not be below 35 to 60°F (varies with mix design);
- Laydown temperatures – One of the most important factors that affect the compaction process is the temperature of the mixture. The range of mix temperature in which

effective compaction can be achieved is 185 to 350°F (85 to 176°C). Mix type, design, surface temperature, air temperature, and layer thickness are factors that influence the rate of temperature decrement. Table 32 presents the recommended compaction time according to the aforementioned variables *[4]*.

Table 32
Recommended compaction time for different construction conditions *[4]*

Lift thickness	**½ in.**	**¾ in.**	**1 in.**	**1-1/2 in.**	**2 in.**	**+3 in.**
Base Temperature	**Mixture Temp (°F)**					
20-32	NA	NA	NA	NA	NA	285
32-40	NA	NA	NA	305	295	280
40-50	NA	NA	310	300	285	275
50-60	NA	310	300	295	280	270
60-70	310	300	290	285	275	265
70-80	300	290	285	280	270	265
80-90	290	280	275	270	265	260
+90	280	275	270	265	260	255
Rolling Time (min)	4	6	8	12	15	15

- Thickness of the lift: The nominal maximum aggregate size (NMAS) of the mixture and the mix type (base or surface course) are two factors that influence the thickness of the lift. The range of lift thickness typically ranges from 0.38 to 3 in. (9.5 to 76 mm). These two limits represent the sizes of the smallest and the largest aggregate. The ratio of lift thickness to NMAS can be estimated according to the thumb rule, which is at least 3:1 for fine mixtures and 4:1 for coarse mixtures.

- Compaction procedures and equipment: Different types of compacting equipment, including vibratory, static steel, static pneumatic rubber, and oscillatory rollers, are used in compaction. The properties of the layer determine the equipment type, the amplitude of the load, and the appropriate frequency. New technologies, such as the smart compaction, can also be used to enhance the quality of compaction in pavement construction *[4]*.

Achieving Smoothness. Reducing the dynamic impacts of vehicles on the pavement, improved ride ability, fuel consumption reduction, and a decrement in vehicle depreciation, are among the various advantages of reaching the desired initial smoothness in pavement construction. Reaching a specific level of initial smoothness is important; studies indicate that pavement with a higher level of initial smoothness can remain smooth for a longer period of time *[4]*.

In recent years, agencies have encouraged the construction of smooth pavements. Variations of mixture temperature, deficiencies in construction, paver speed changes, segregation, and inappropriate rolling, can all negatively impact the smoothness of the pavement. North Carolina DOT has offered important guidelines to achieve the desired level of initial smoothness in pavement construction:

- Paving operation should be conducted continuously to avoid paver stoppage.
- Lower layers should be treated to resolve irregularities.
- The paver needs to be continuously supplied in order to avoid rough surfaces.

Quality Assurance in Pavement Construction

Quality assurance (QA) is a set of activities to guarantee that the materials and construction operations satisfy the project requirements. Different categories, such as appropriate lay-down and compaction of all layers, and specifying smoothness standards are included in these project requirements. Constructing the pavement based on these standards can lead to a lower maintenance cost and less environmental impacts related to these activities.

Generally, applying QA plans enhances the quality of pavement construction and materials. Asphalt concrete construction phases, which include production, placement and compaction, are usually covered by QA. Soil density, environmental and mix temperature, thicknesses of layers, joint building, segregation, in-place density, and smoothness are factors that are also considered in QA specifications for asphalt pavement construction *[4]*.

Percent within limits is a kind of statistical method used by highway agencies to evaluate the pavement quality by evaluating the percentage of the quality characteristic that lies within the specification limit. The PWL analysis output can be utilized to specify the pay factors according to the predicted effects of the specified quality characteristics related to the performance of the pavement *[4]*. In-place density and initial smoothness are among the prevalent quality characteristic factors that can be applied in order to implement PWL analysis in asphalt pavement. Therefore, it is assumed that long-term pavement performance is function of quality characteristics. Real-time monitoring should be applied to gage some of the most important quality characteristics. Therefore, there is a need to develop methods and equipment that can be implemented in the field such as utilizing ground penetrating radar (GPR), intelligent compaction (IC) technology, and Infrared Thermography (IRT) *[4]*.

Profile testing methods are used to quantify the smoothness of as-constructed pavements. Inadequate smoothness can increase fuel consumption drastically and influence the rideability of the pavement, which makes it one of the most critical pay items.

Sustainability Improvement by Applying Innovative Technologies. Traditional density measurement methods, such as field-extracted cores and nuclear density gauge measurements are destructive and provide limited information because of limited number of test locations *[4]*.

Applying methods like GPR and IRT, which are non-destructive, can be used to monitor pavement construction quality. The GPR method can cover a larger area of testing, which in turn results in more comprehensive density results. Furthermore, real-time monitoring is applicable to compaction processes and can be calibrated for a particular type of aggregate, which leads to higher accuracy. Figure 41 illustrates continuous density measurements by applying the GPR method.

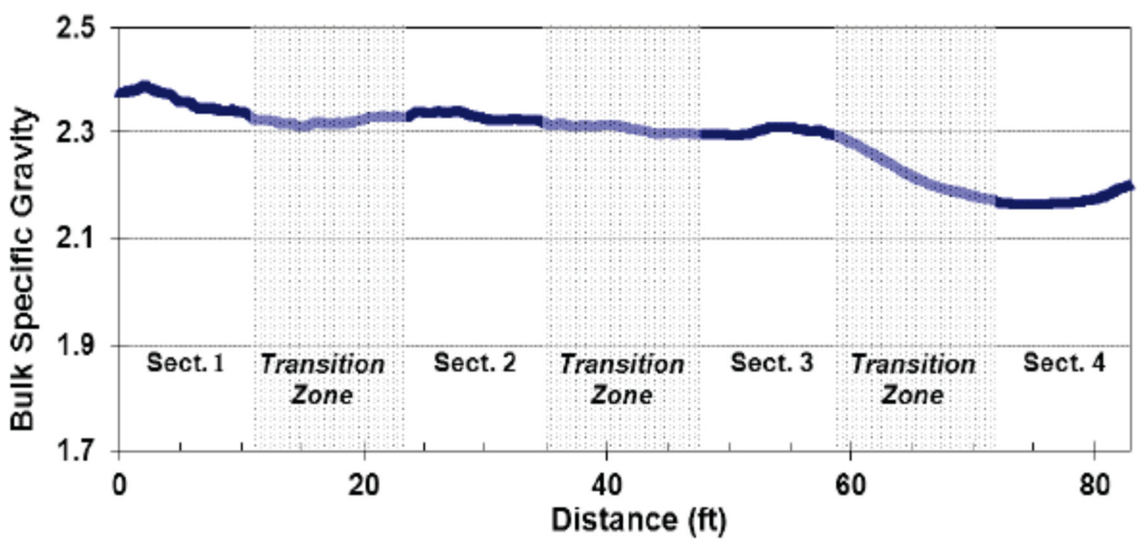


Figure 41
Density variation from GPR measurements *[4]*

The temperature of the whole asphalt pavement must be consistent in order to achieve adequate compaction of the paving mat. This can be detected by temperature scanning systems, such as an infrared thermography *[4]*. Intelligent compaction is another innovative QA approach, which can be used during pavement construction. There are clear differences between traditional compaction systems and intelligent compaction equipment. IC systems are usually equipped with a double-drum vibratory roller, which includes a GPS and a system for temperature measurements *[4]*.

Superior construction quality can also be achieved by using spray pavers and MTVs. By using a spray paver, which can act as a conventional paver and a tack coat distributor concurrently, the tack coat can be laid immediately before asphalt placement. This approach offers numerous benefits, such as decrement of using distributer vehicle, avoiding contamination, and saving time. MTVs were found to enhance pavement construction by decreasing the chance for segregation and temperature fluctuation and maintaining material uniformity *[4]*.

Methods to Improve Sustainability in Concrete Pavement Construction Phase

Generally, construction activities for concrete pavement involve the following:

- Subgrade preparation activities such as excavation, compaction, aggregate deposition, and relative treatments;
- Base and subbase preparation by trimming, compacting, and curing the layers;
- Production; hauling, and concrete mix placement;
- Finishing, texturing, and curing of the concrete pavement.

The aforementioned activities as well as typical fuel consumption factors are illustrated in Figure 42. Sustainability improvement activities can be applied through the different construction phases. A cost analysis of each stage may also improve project construction efficiency.

Concrete Pavement
Base Course (optional)
Subbase course (optional)
Subgrade Layer(s)

Construction Activity	*Fuel Factor*
Subgrade Preparation (grading and finishing)	0.300-0.700 gals/cubic yard
Base Layer Preparation (hauling, placement, and compaction)	0.400-0.600 gals/ton
Concrete Mix Production	0.09 gals/c.y.
Concrete Hauling (short)	0.60 gals/c.y.
Concrete Placement	0.267 gals/c.y.

Figure 42
Concrete pavement activities and the related fuel consumption factor *[4]*

Sustainable practices in the design stage should be implemented by a proper pavement construction plan. For example, sustainable practices for long-life pavement, which benefits from an optimized structure, as well as high resistant materials, can become inefficient by implementing inappropriate construction strategies. Therefore, it is necessary to consider both environmental and service life impacts of the pavement associated with the construction activities. A summary of sustainable practices for concrete pavement is presented in Table 33.

Table 33
Summary of sustainable practices in concrete pavement construction *[4]*

Objectives	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Protect Water Resources	Concrete wash water collection and reuse	Increased cost for collection and removal, but reduced costs of remediation and clearing drains.	Positive impact by eliminating localized vegetation kills and pH impact on local surface waters.	Negligible to slightly positive impact
Reduce Use of Virgin Materials	On-Site Recycling	Reduced haul costs, reduced material costs.	Reduced fuel consumption, reduced GHGs, reduced consumption of resources.	Negligible to slightly positive impact
	Two-Lift Paving	Negligible to slightly higher construction costs.	More energy consumed in construction, improved use of local and recycled materials, potential reductions in use-phase fuel consumption and GHGs.	Negligible to slightly positive impact
Improve Initial Ride Quality (Minimize Use-Phase Fuel Consumption	Two-Lift Paving	Negligible to slightly higher construction costs.	More energy consumed in construction, improved use of local and	Positive impact of improved ride quality, reduced use-phase costs for vehicles.

and Emissions			recycled materials, potential reductions in use-phase fuel consumption and GHGs.	
	Real-Time Profile Measurement	Capital cost of equipment	Potential reductions in use-phase fuel consumption and GHGs.	Positive impact of improved ride quality, reduced use-phase costs for vehicles.
Increase Pavement Service Life	Improved Construction QA (including Dowel Alignment Measures) Good Curing Materials and Practices	Additional testing costs. Negligible to modest increase in construction costs.	Potential for longer life cycle	Potential for extended time between maintenance activities, longer life cycle, and lower user costs.
Balance Surface Friction and Tire-Pavement Noise	Selection and Design of Surface Texture	Negligible to modest increase in construction costs (depending upon surface texture selected).	Potential to reduce tire-pavement noise inside and outside of vehicles.	Potential for improvements in friction, safety
Minimize Construction Fuel Use and Emissions	On-Site Recycling (Foundation Layers)	Reduced haul costs, reduced material costs.	Reduced fuel consumption, reduced GHGs, reduced consumption of resources.	Negligible to slightly positive impact
	Match Construction Equipment and Production Capacities	Cost savings	Reduced fuel consumption and GHGs, less wasted material.	Minor impact

	Single-Lift Construction	Cost savings over multi-lift construction processes	Lower fuel consumption and GHG emissions.	Negligible to favorable impact, depending upon time savings.
	Use Roller-Compacted Concrete	Significant construction cost savings (mainly due to materials)	Lower fuel consumption and GHG emissions in construction	Minimal impact for low-speed pavements; generally inadequate ride quality (without overlay or diamond grinding) for high-speed roadways
	Use Early Entry Saws	Reduced cost	Reduced construction fuel consumption and GHG emissions.	Negligible

Site Preparation Activities. Appropriate grading and consistent compaction, which are important factors in determining long-time pavement performance, can be achieved by designing an accurate platform in order to reach a suitable grading and to ensure long-term rideability and distress resistance as well. According to studies, there is a direct relationship between the rideability and long-time pavement performance *[4]*.

Installation of Dowels, Tie Bars, and Slab Reinforcement. The necessary components of concrete pavements include dowels, tie bars, and slab reinforcement. In order to achieve the best performance, these items must be installed at the appropriate distance. For instance, a very small spacing between the pavement surface and the reinforcing steel may damage the surface of the concrete pavement, which is difficult and expensive to repair. There are five different possibilities for dowel misalignment, such as three translational modes, and two rotational modes. Different types of impacts are associated with each of these misalignments. For instance, surface spalling and joint faulting distress commonly appear due to tie bar misalignment *[4]*.

To guarantee the accuracy of dowel bars and slab reinforcements, certain points, including check of placement equipment, appropriate placement of baskets and support components, adequate anchoring of basket and support systems (to avoid movement and overturning during construction), and proper joint location and sawing procedures should be considered. Using rebar, which are resistant to corrosion, is a critical objective during the design phase and construction stage *[4]*.

In order to enhance the durability of concrete pavements, stringline conservation, plant certification, appropriate equipment arrangement (such as haul time limitations based on the temperature), appropriate mixing of the concrete (to prevent segregation and keep ahead the paver load constant), managing water consumption at the site, appropriate materials quality assurance (such as controlling mixture consistency through air, slump and unit weight testing, thickness control, durability, and maturity testing), are critical to be considered in quality assurance processes *[4]*.

Sustainability Enhancement by Utilizing Innovative Approaches and Technologies. Concrete is typically placed in one layer, which is called a single-lift method. Two-lift paving is another approach for placing the concrete. Therefore, placing two layers of concrete on each other (wet-on-wet) can provide some advantages in rideability, simplifies utilization of recycled materials and SCMs in the underneath layer, and reduces construction expenses *[4]*. The first concrete pavement constructed by the two-lift concrete placing approach was in Ohio. This method was also used in jointed reinforced concrete pavements (JRCP). The great potential of enhancing sustainability in the pavement industry, observed in different European countries, encouraged practitioners in the U.S. to implement this approach in pavement construction *[4]*.

Roller Compacted Concrete. Roller Compacted Concrete (RCC) is a compacted concrete mixture, compacted by appropriate tools, and without slump. The major constituents of RCC are identical to traditional concrete mixtures. The only difference is the applied, mixed design uses a higher amount of fine aggregate, less cement and a relatively small W/C (Water/Cement) ratio. In this type of mixture, a transverse joint is usually sawed at a longer spacing and dowel bars cannot be used. Aggregate interlocking can provide a load transferring function through the transverse cracks *[4]*.

Pavement constructed by RCC methods can immediately endure light vehicles when being initially compacted by proper tools. Furthermore, cement hydration can ensure adequate long-term pavement performance. The cost analysis of RCC depicts that the cost of the pavement is reduced due to a lower water/cement ratio, while the load bearing capacity and durability of the pavement remain higher than traditional concrete pavements. The other advantage of RCC compared with traditional concrete is the ability to endure a light traffic load immediately after the placement process, thus avoiding the usual traffic congestion during normal construction processes *[4]*.

Measuring Real-Time Smoothness. To measure the profile of concrete pavement, which is beneficial to determine rideability and smoothness, there is a need to wait for the hardening phase to be complete. There are two major drawbacks associated with this type of measurement. First, it is not possible to find the causes of the profile problems, in order to prevent future problems. Second, the measurement process can be affected by joint forming and pavement texturing *[4]*.

Real time measurement can be accomplished through non-contact procedures by avoiding the delays of conventional texture measurements. Real-time measurement allows construction amendments to be completed in order to have a better surface profile during the rest of the construction process. In addition, the subgrade profile can be checked with devices, which are usually used for profile measurements *[4]*. This measurement tool can enhance sustainability, by means of the smoothness improvement as well as reducing maintenance and rehabilitation activities.

APPENDIX F

Survey Conducted in Louisiana and its Result

None of the Louisiana-based companies had published their individual EPDs. Therefore, a survey was conducted to determine if the companies measured any type of inventory data of their products. The survey resulted that a total of seven companies with 48 plants participated in the NRMCA industry-wide average EPD program. Among those companies, only five companies with 16 plants were included to develop the industry-wide average EPD. Further, the collected inventory data were not statistically representative and therefore were aggregated with the other data from the south-central region. The Institutional Review Board (IRB) at Louisiana State University (LSU) supervised the survey, which consists of the following sections:

- *Project Description:* The information about the project along with the link for more detailed information was provided in the first page.
- *A guide to consent form:* Under this section, the purpose of the research, information about project personnel/investigators, data sensitivity, the study procedure, the risk involved in the participation and right to refuse to participate was included.
- *Survey Questionnaire:* This section consists of a list of questions for the survey.

Each section is presented next.

Product Description

The aim of this research is to provide the Louisiana Department of Transportation and Development (DOTD) with a user-friendly decision-making tool for quantifying the sustainability of pavement designs.

To achieve this objective, this survey aims to collect data related to life-cycle environmental impact and inventory data for concrete products produced in Louisiana. The collected data will be integrated into the pavement Mechanistic-Empirical design framework, as a sustainability input and the overall design will be evaluated based on performance, environmental and economic criteria.

More information about the project can be found in this website: http://www.ltrc.lsu.edu/pdf/2016/capsule_17-3P.pdf

Guide to Consent

1. Name and contact information of the investigator(s)

The researchers conducting this survey are:

Neveen Soliman. Please direct any questions you have to ntalaa1@lsu.edu

Co-investigator: Prof. Marwa Hassan

Contact information: marwa@lsu.edu

2. Purpose of the research and data sensitivity

The purpose of this research is to measure/assess life cycle category indicators and inventory metrics in Louisiana Plants producing concrete.

The answers to this survey might be sensitive. However, the data will be kept confidential.

3. Study procedures

To participate in this study:

1) your plant should be in Louisiana, and

2) you should be mixing and manufacturing concrete.

You will be asked to fill in a survey about your concrete plant located in Louisiana. The purpose is to collect data about life cycle category indicators and inventory metrics. If you performed these measurements, please provide them. If you did not perform any of these measurements, please state the reason.

4. Risk involved in participation

There is no risk involved in this study except for data sensitivity. However, the data will be kept confidential.

5. Inform the participants of their right to refuse

"Subjects may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which they might otherwise be entitled."

Survey Questionnaire

Section 1: General information

1. Please provide information about your company.

Company name
Company address
Street
City
State
Zip code

2. Please provide information about your plant, located in Louisiana.

Plant name
Plant address
City
State
Zip code

3. Please provide information about the preparer.

Name of the preparer
Position
Contact information

Section 2: Measurement

4. Please indicate if you measured the following life-cycle environmental impact data/inventory metrics in your plant for the produced concrete mix designs.

- ☐ Global Warming Potential
- ☐ Acidification Potential
- ☐ Eutrophication Potential
- ☐ Ozone Depletion Potential
- ☐ Photochemical Ozone Creation Potential
- ☐ Total primary energy consumption
- ☐ Depletion of non-renewable energy resources
- ☐ Use of renewable primary energy
- ☐ Depletion of non-renewable material resources
- ☐ Use of renewable material resources
- ☐ Concrete batching water consumption
- ☐ Concrete washing water consumption
- ☐ Total water consumption
- ☐ Concrete hazardous waste
- ☐ Concrete non-hazardous waste
- ☐ None of the above

If you selected on any of the options in question 4, please proceed to section 3 and 4.

5. If the answer to the above is "none of the above." Please indicate the reason.

- ☐ The plant is small
- ☐ Not required per regulation
- ☐ All the above
- ☐ Other: Please indicate

Section 3: Mix Design Properties

Please provide information about the mix designs produced in your plant, for which you measured any of the impacts as selected in Question 4 in section 2.

Table 34
Mix design chart for plant products

Mix Design Id	Compressive Strength Value (psi)	Cement (lb)	Fly ash (lb)	W/C ratio	Coarse Aggregate (lb)	Fine Aggregate (lb)	Slump (inch)	Air (%)	Nominal maximum Aggregate Size (inch)

Section 4: Life-Cycle environmental impact data/inventory metrics

Please provide information about life-cycle environmental impact data/inventory metrics measured for the mix designs in section 3.

Table 35
Inventory data collected for plant mixes

Impact Category	Unit	Value
Mix ID:		
Global Warming Potential		
Acidification Potential		
Eutrophication Potential		
Ozone Depletion Potential		
Photochemical Ozone Creation Potential		
Total Primary Energy Consumption		
Depletion of non-renewable energy resources		
Use of renewable primary energy		
Depletion of non-renewable material resources		
Use of renewable material resources		
Concrete batching water consumption		
Concrete washing water consumption		
Total Water Consumption		
Concrete non-hazardous waste		

Section 5: Other information (optional)

Please provide any information that you find useful or anything you want to add apart from the above mentioned one.

The list of the seven companies (48 plants) that participated in the NRMCA industry-average program are listed in Table 36.

Table 36
Companies participated in NRMCA industry-average program

S. No.	Company Name	Plant Name
1	Angelle Materials	Denham Springs
2	Angelle Materials	Westport
3	Angelle Materials	Zachary
4	Angelle Materials	Choctaw
5	Angelle Materials	Gonzales
6	Angelle Materials	Plaquemine
7	Builder's Supply	Forth Street Plant
8	Builder's Supply	Minden Plant
9	Builder's Supply	Natchitoches plant
10	Builder's Supply	Viking Drive Plant
11	Builder's Supply	Armistead Plant
12	Builder's Supply	Industrial Drive Plant
13	Builder's Supply	Fairview Alpha Plant
14	Builder's Supply	Homer Plant
15	Builder's Supply	Mansfield Plant
16	Builder's Supply	Brooks Road Plant
17	Builder's Supply	St Vincent Plant
18	Builder's Supply	West 70th Plant
19	Builder's Supply	Springhill Plant
20	Builder's Supply	Winnfield Plant
21	CEMEX Inc.	Bessemer-CEMCO #7
22	CEMEX Inc.	CEMCO #3 Calera
23	Delta Industries, Inc.	Amite Ready-Mix Plant #12
24	Dolese Brothers	South Choctaw Batch Plant
25	Dolese Brothers	Choctaw Batch Plant
26	Dolese Brothers	Zachary Batch Plant
27	Dolese Brothers	New Roads Batch Plant
28	Dolese Brothers	Dow Batch Plant
29	Dolese Brothers	Prairieville Batch Plant
30	Lafarge North America	Covington
31	Lafarge North America	Engineers Road
32	Lafarge North America	Fourchon
33	Lafarge North America	Gramercy
34	Lafarge North America	Hammond

35	Lafarge North America	Houma
36	Lafarge North America	Airport
37	Lafarge North America	Larose
38	Lafarge North America	Luling
39	Lafarge North America	Choctaw
40	Lafarge North America	West bank
41	Lafarge North America	Metairie
42	Lafarge North America	Earhart
43	Lafarge North America	New Orleans East
44	Lafarge North America	Slidell
45	Lafarge North America	Thibodaux
46	Martin Marietta	Martin Marietta #180 Jonesville
47	Martin Marietta	Martin Marietta #194 Monroe B
48	Martin Marietta	Martin Marietta #187 West Monroe

Out of these companies, only five companies with 16 plants were included for the development of Louisiana-based industry-wide average EPD. This was done due to lack of representative data of those excluded companies.

The mix design collected from the companies consist of information on the content and type of raw materials such as cement, slag fly ash, coarse aggregate 1, coarse aggregate 2, fine aggregates, water, water/cement ratio water reducer, air entertainer, set accelerator, super plasticizer, special additives (A, B, & C). The summary of the type of raw materials is presented in Table 37.

Table 37
Type of Material in the mix design of industry products

Material	Type
Cement	Type 1 or Type 2
Fly Ash	Class C
Slag	None of the collected mixes contain slag
Fine Aggregate	Fine Aggregate (concrete sand)
Coarse Aggregate 1	Grade A coarse aggregate (Stone) and Grade A coarse aggregate (Stone)
Coarse Aggregate 2	Grade F and Grade A coarse aggregate (Stone aggregate)

APPENDIX G

Inventory Data for Trucks Used in the Transportation Module

Table 38
Inventory data for Light commercial truck, gasoline powered per (tonne.km)

Flow	Category	Flow Type	Unit	Amount	Remarks
Outputs					
Ammonia	air/unspecified	Elementary	kg	3.95E-05	
Carbon dioxide, fossil	air/unspecified	Elementary	kg	5.39E-01	
Carbon monoxide, fossil	air/unspecified	Elementary	kg	1.46E-02	
Hydrocarbons	air/unspecified	Elementary	kg	1.19E-03	
Methane	air/unspecified	Elementary	kg	5.42E-05	
Nitrogen dioxide	air/unspecified	Elementary	kg	1.74E-04	
Nitrogen oxide	air/unspecified	Elementary	kg	1.56E-03	
Nitrogen oxides	air/unspecified	Elementary	kg	1.73E-03	
Nitrous oxide	air/unspecified	Elementary	kg	4.06E-05	
Particulates, < 10 um	air/unspecified	Elementary	kg	6.02E-06	PM10 from break wear
Particulates, < 10 um	air/unspecified	Elementary	kg	1.94E-05	PM10 from organic compound, elemental carbon, and sulfate particulates
Particulates, < 10 um	air/unspecified	Elementary	kg	1.96E-05	PM 10 from tire wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	1.44E-06	PM 10 from tire wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	5.12E-06	PM10 from break wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	1.79E-05	PM10 from organic compound, elemental carbon, and sulfate

					particulates
Sulfur dioxide	air/unspecified	Elementary	kg	1.05E-05	
VOC, volatile organic compounds	air/unspecified	Elementary	kg	1.22E-03	
Inputs					
Gasoline, at refinery	Petroleum and Coal Products	Product	l	2.32E-01	

Table 39
Inventory data for single unit truck, gasoline powered per (tonne.km) data

Flow	Category	Flow Type	Unit	Amount	Remarks
Outputs					
Ammonia	air/unspecified	Elementary	kg	9.83E-06	
Carbon dioxide, fossil	air/unspecified	Elementary	kg	2.56E-01	
Carbon monoxide, fossil	air/unspecified	Elementary	kg	1.00E-02	
Hydrocarbons (other than methane)	air/unspecified	Elementary	kg	4.78E-04	
Methane	air/unspecified	Elementary	kg	3.56E-05	
Nitrogen dioxide	air/unspecified	Elementary	kg	7.67E-05	
Nitrogen oxide	air/unspecified	Elementary	kg	8.93E-04	
Nitrogen oxides	air/unspecified	Elementary	kg	9.70E-04	
Nitrous oxide	air/unspecified	Elementary	kg	1.51E-05	
Particulates, < 10 um	air/unspecified	Elementary	kg	1.28E-05	PM10 from break wear
Particulates, < 10 um	air/unspecified	Elementary	kg	5.23E-06	PM10 from organic compound, elemental carbon, and sulfate particulates
Particulates, < 10 um	air/unspecified	Elementary	kg	2.51E-06	PM 10 from tire wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	4.81E-06	PM 10 from tire wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	6.03E-07	PM10 from break wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	3.36E-06	PM10 from organic compound, elemental carbon, and sulfate particulates
Sulfur dioxide	air/unspecified	Elementary	kg	4.99E-06	
VOC, volatile organic compounds	air/unspecified	Elementary	kg	1.00E+00	
Inputs					

Gasoline, at refinery	Petroleum and Coal Products Manufacturing/ Petroleum Refineries	Product	l	1.1E-01	

Table 40

Inventory data for combination truck, gasoline powered per (tonne.km) data

Flow	**Category**	**Flow Type**	**Unit**	**Amount**	**Remarks**
Outputs					
Ammonia	air/unspecified	Elementary	kg	1.96E-06	
Carbon dioxide, fossil	air/unspecified	Elementary	kg	8.41E-02	
Carbon monoxide, fossil	air/unspecified	Elementary	kg	8.14E-03	
Hydrocarbons (other than methane)	air/unspecified	Elementary	kg	3.75E-04	
Methane	air/unspecified	Elementary	kg	2.57E-05	
Nitrogen dioxide	air/unspecified	Elementary	kg	2.15E-05	
Nitrogen oxide	air/unspecified	Elementary	kg	7.33E-04	
Nitrogen oxides	air/unspecified	Elementary	kg	7.55E-04	
Nitrous oxide	air/unspecified	Elementary	kg	2.94E-06	
Particulates, < 10 um	air/unspecified	Elementary	kg	4.14E-07	PM10 from break wear
Particulates, < 10 um	air/unspecified	Elementary	kg	9.49E-06	PM10 from organic compound, elemental carbon, and sulfate particulates
Particulates, < 10 um	air/unspecified	Elementary	kg	1.52E-06	PM 10 from tire wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	8.74E-06	PM 10 from tire wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	9.94E-08	PM10 from break wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	3.98E-07	PM10 from organic compound, elemental carbon, and sulfate particulates
Sulfur dioxide	air/unspecified	Elementary	kg	1.56E-06	
VOC, volatile organic compounds	air/unspecified	Elementary	kg	3.84E-04	
Inputs					

Gasoline, at refinery	Petroleum and Coal Products Manufacturing/ Petroleum Refineries	Product	1	3.67E-02	

Table 41
Inventory data for single unit truck, diesel powered per (tonne.km) data

Flow	Category	Flow Type	Unit	Amount	Remarks
Outputs					
Ammonia	air/unspecified	Elementary	kg	5.90E-06	
Carbon dioxide, fossil	air/unspecified	Elementary	kg	2.63E-01	
Carbon monoxide, fossil	air/unspecified	Elementary	kg	6.57E-04	
Hydrocarbons	air/unspecified	Elementary	kg	1.49E-04	
Methane	air/unspecified	Elementary	kg	7.19E-06	
Nitrogen dioxide	air/unspecified	Elementary	kg	1.36E-04	
Nitrogen oxide	air/unspecified	Elementary	kg	1.20E-03	
Nitrogen oxides	air/unspecified	Elementary	kg	1.33E-03	
Nitrous oxide	air/unspecified	Elementary	kg	7.50E-07	
Particulates, < 10 um	air/unspecified	Elementary	kg	1.53E-05	PM10 from break wear
Particulates, < 10 um	air/unspecified	Elementary	kg	7.42E-05	PM10 from organic compound, elemental carbon, and sulfate particulates
Particulates, < 10 um	air/unspecified	Elementary	kg	3.16E-06	PM 10 from tire wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	7.20E-05	PM 10 from tire wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	7.57E-07	PM10 from break wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	4.02E-06	PM10 from organic compound, elemental carbon, and sulfate particulates
Sulfur dioxide	air/unspecified	Elementary	kg	4.28E-06	
VOC, volatile organic compounds	air/unspecified	Elementary	kg	1.54E-04	
Inputs					
Diesel, at refinery	Petroleum and Coal Products	Product	l	1.00E-01	

Table 42
Inventory data for combination truck, diesel powered per (tonne.km) data

Flow	Category	Flow Type	Unit	Amount	Remarks
Outputs					
Ammonia	air/unspecified	Elementary	kg	1.18E-06	
Carbon dioxide, fossil	air/unspecified	Elementary	kg	9.22E-02	
Carbon monoxide, fossil	air/unspecified	Elementary	kg	1.42E-04	
Hydrocarbons	air/unspecified	Elementary	kg	2.71E-05	
Methane	air/unspecified	Elementary	kg	7.28E-07	
Nitrogen dioxide	air/unspecified	Elementary	kg	4.76E-05	
Nitrogen oxide	air/unspecified	Elementary	kg	5.15E-04	
Nitrogen oxides	air/unspecified	Elementary	kg	5.62E-04	
Nitrous oxide	air/unspecified	Elementary	kg	9.49E-08	
Particulates, < 10 um	air/unspecified	Elementary	kg	2.39E-06	PM10 from break wear
Particulates, < 10 um	air/unspecified	Elementary	kg	2.82E-05	PM10 from organic compound, elemental carbon, and sulfate particulates
Particulates, < 10 um	air/unspecified	Elementary	kg	7.42E-07	PM 10 from tire wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	2.74E-05	PM 10 from tire wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	1.78E-07	PM10 from break wear
Particulates, < 2.5 um	air/unspecified	Elementary	kg	6.25E-07	PM10 from organic compound, elemental carbon, and sulfate particulates
Sulfur dioxide	air/unspecified	Elementary	kg	1.53E-06	
VOC, volatile organic compounds	air/unspecified	Elementary	kg	2.79E-05	
Inputs					
Diesel, at refinery	Petroleum and Coal Products	Product	l	3.51E-02	

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