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An Approach for Performing Life Cycle Impact Assessment of Pavements for Evaluating Alternative Pavement Designs

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Abstract

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

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1. Introduction

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

Researchers have proposed to evaluate environmental impacts of alternate pavement designs using Life Cycle Assessment (LCA) approach [1]. LCA comprehensively quantifies the emissions and energy flows of a product (pavement) in its Life Cycle. International organization of standardization (ISO) released two standards ISO-14040 2006 and ISO-14044 2006 to standardize the LCA methodology. Similar to ISO standards, detailed procedure for conducting of LCA has been proposed by United States Environment Protection Agency (US EPA) document [2]. Even though LCA has been proposed by these agencies, they do not specifically provide guidance for performing LCA of pavements [3].

Various researchers have performed pavement LCA [4,5,6,7,8,9,10,11,12,13,14] based on ISO standards. The consensus phases of LCA and life cycle of pavement are shown in Fig.1. Although proposed phases of LCA suggests Life Cycle Impact Assessment, the studies mainly focused on estimating the emissions inventory by collecting data from numerous sources. Additionally, studies devoted significant time in accounting the emissions from all phases of pavements while placing little or no emphasis on impact assessment. It is essential for decision makers to understand the true sense of the characterized impacts because these numbers will be used in selecting a design. Aggregated impact categories or emission inventories may be better interpreted by placing them in an adequate environment context [15]. The normalization and weighting steps of LCIA aims at addressing these issues and is focus of this study.

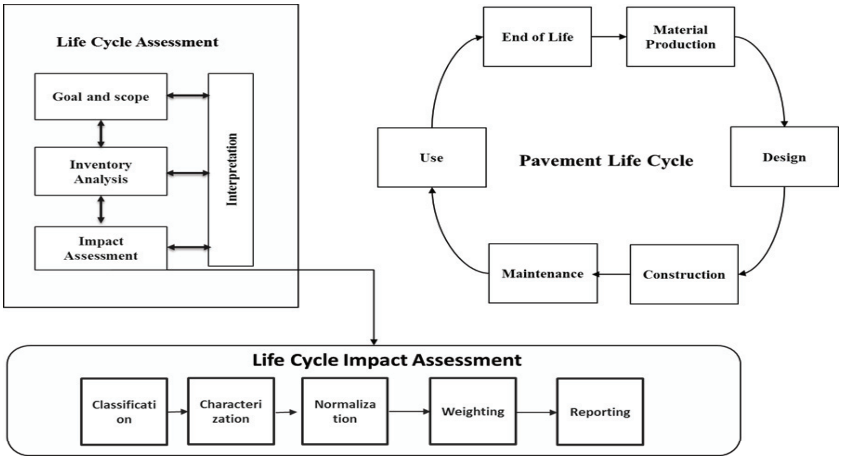

Fig. 1. Framework for LCA, LCIA and Pavement Life Cycle.

2. Objectives

The principle of normalization is to associate the characterized results of pavement to a common scale that is familiar and understandable to decision makers. The drawback of disregarding the normalization step in the LCIA is that the decision makers may place unnecessary importance on insignificant data leading to making inappropriate choices [16]. Ultimately, all the efforts placed on conducting LCA will be futile if the decision makers chose an inappropriate design. Considering the importance of normalization in LCA, this study proposes to address the following objectives:

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

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

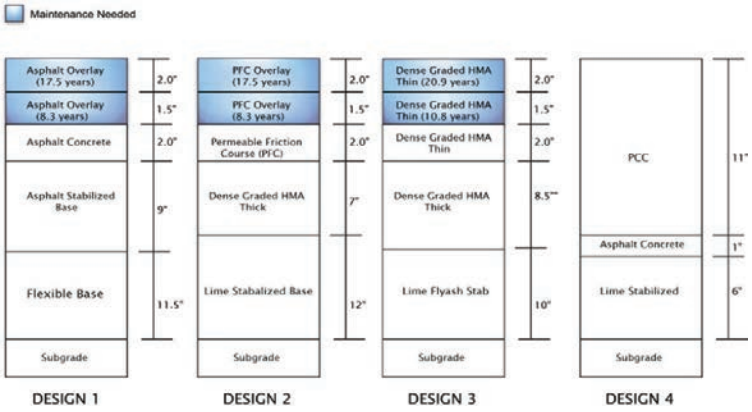

Fig. 2. Alternative Pavement Designs

3. Approach

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

3.1. Goal and Scope of LCA

The goal of the present study is to assist decision makers in selecting structural designs of pavements which produces minimal environmental impact. Typically, a pavement life cycle consists of different phases such as material extraction and production, design, construction, maintenance, use, and end of life as shown in Fig. 1. A complete LCA study should include emissions from all these phases. However, Use phase, End of life phase and equipment manufacture emissions were not included in this study. The goal of this study is to differentiate various pavement designs and there are no well-established models that can assess the emissions from various pavement surfaces during use phase. Even though rolling resistance was used by Santero et al. [10], there are uncertainty in the predicting models, hence, use phase is ignored in this study. End of life poses a unique burden on the environment but, for pavements especially high volume highways, there is no well-defined end of life where the pavement would be removed and thrown away [4]. In addition, emissions due to manufacturing of construction equipment were not considered because the construction equipment has a substantial life and allotting the manufacturing emissions for a particular project will be in appropriate.

3.2. Life Cycle Inventory

In inventory phase, data is collected based on goal and scope definition. In this study, a process approach LCA was employed to account for various emissions during material extraction and manufacturing, transportation, and construction of alternative pavement designs. In process approach, the inputs and emissions for each discrete process within a life cycle system boundary are quantified rather than reference values obtained from the published literature. In this study, various inventory models were selected based on the reliability of emission data and feasibility to employ in pavement LCA and are discussed in the following paragraphs. Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) life cycle model was employed to estimate the emissions from the material extraction and manufacturing phase as well as the transportation phase. GREET models provide upstream life cycle emissions for all fuels and the majority of the construction materials. In the GREET model, the user can develop their own processes or can modify existing processes for estimating emissions to replicate the actual process. For this study, a hauling distances 50 miles to the plants and 12 miles from plants to construction site were assumed for all materials (cement, asphalt, aggregates, diesel etc.).

The traffic delay emissions during maintenance operations were estimated using Motor Vehicle Emission Simulator (MOVES) 2014. It was also assumed that maintenance happens from 9AM—5PM and one lane on each side of pavement was closed. Emissions due to traffic delays during initial construction and emergency maintenances were not considered in this study. Construction equipment emissions during operation are drawn from the EPA's NONROAD model which is embedded in MOVES 2014 [17]. The type of equipment and working hours of equipment were estimated based on the RSMeans data [18] for the El Paso, Texas, region. The inventory data of various pollutants for the four pavements shown in Fig.2, are displayed in the Table 1.

Table 1. LCI of four Pavement Designs per mile Length.

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

3.3. Life Cycle Impact Assessments

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

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

3.4. Normalization

Normalization relates the aggregated impact categories of an LCA to the macro world in which the service / product is surrounded [19]. Generally, normalization is a process of converting different numbers into common unit numbers.

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

- It aids decision makers in understanding the characterized impact data.
- It makes easier to make comparisons between impact scores of different impact categories [20].
- It expresses the relative magnitude of the impact scores on a scale that is common to all the categories of impact [21].
- It serves as a means for preparation of weighing, which is the final step in LCIA [22]

Table 2. Characterized and Normalized Factors.

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

Table 3. Characterized Impact Categories for Alternative Designs.

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

Even though normalization step in LCIA have benefits, the normalization process have some setbacks. Currently, the key problem in normalization process is the selection of reference system. The selected reference system should be in harmony with the goal and scope of any study. In this study, the characterized data in Table 3 was normalized using two reference systems: 1) US per capita normalized factors [23] and 2) Passenger car normalized factors [24]. The normalized data that uses normalized factors of Table 2 is shown in Fig 3.0.

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

[†] Characterization factors were taken from US EPA’s LCIA model called TRACI

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

“-“ not applicable

One can perceive the importance of selecting the reference system and possibility of misleading, if normalized data is used to compare impact categories. Considering the subjectivity involved in selection of reference system, there is a need to develop sector specific reference system. A specific reference system exclusively for pavements is not available currently, which leads to use of the existing reference systems.

The alternate way to alleviate the problem of reference system is to use internal normalization, i.e., comparing one design with the other. Internal normalization does not require any reference system. A simple normalization technique is used in this study to explain the internal normalization process. The characterized data in Table 3 is normalized by dividing the each design impact category results with the maximum among the group of alternate designs as shown in Table 4. Each design has an impact category score from 0 to 1. For example, D1 has GWP score of 1 and D4 has 0.42, which implies that D4 emitted only 42 percent of GWP compared with D1.

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

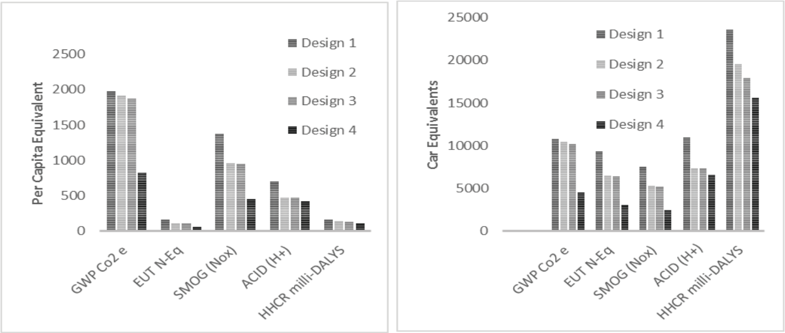

Fig. 3. Normalized Data for US/ Capita emissions in 2008 and for Car Emissions.

Table 4. Internal Normalization Results.

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

3.5. Weighting

The reason for employing weighting is to simplify LCIA output. Weighting in LCIA aspires at rating different impact categories against each other to determine their significance with respect to the context of conducting LCA [25]. As LCA involves numerous impact categories and each impact categories differs from other in their characteristics, Multi Criteria Decision Analysis (MCDA) is one of the useful tools in assigning the weightages. Gloria et al. [26] calculated the weightages of various impact categories by employing Analytic Hierarchy Process (AHP) which is an MCDA method. They obtained input from users, producers, and LCA experts over the weightage of various impact categories. The weightages proposed by Gloria et al. were used in this study.

The weightages created were specifically in the context of assisting environmentally preferable purchasing of building products in the United States [26]. Although applying the same weightages for selection of pavements may be inappropriate, the same weightages were chosen in this study to demonstrate the relation between weighting and normalization. Authors encourage developing the weightages for impact categories for each study independently.

All impact categories were normalized to both per capita equivalents and passenger car equivalents. Since, all impact categories have similar unit, an overall environmental impact score can be evaluated by linear weighted aggregation of normalized data. For example, impact score of Design 1 (IS1) shown below is 1,146 residents' equivalent. In other words, the impacts for D1 for one mile is equivalent to impacts on 1146 US residents in 2008. The impact scores (people equivalents) for all designs were $[IS_1, IS_2, IS_3, IS_4] = [1146, 1062, 1035, 489]$. By employing the similar approach the impact scores (car equivalents) for all designs were $[IS_1, IS_2, IS_3, IS_4] = [16497, 14121, 13341, 9164]$.

$$IS_1 = (1982 \times 0.475) + (155 \times 0.098) + (1378 \times 0.066) + (698 \times 0.049) + (160 \times 0.148) = 1146$$

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

Table 5. Final Weightage Calculations.

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

4. Conclusions and Discussions

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

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

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

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