Computational Research Progress in Applied Science & Engineering
©PEARL publication, 2017

ISSN 2423-4591

CRPASE Vol. 03(02), 71-80, June 2017

Developing an Index to Measure Sustainability of Road Related Projects Over the Life Cycle

Alireza Samiadel, Amir Golroo*

Department of civil engineering, Amirkabir University of Technology, Tehran, Iran

Keywords

Life cycle cost analysis, road, Sustainability index, Analytical hierarchy process.

Abstract

The life cycle cost analysis (LCCA) of road related projects commonly considers financial investment required for the design, construction, implementation, maintenance, rehabilitation and end of life. Although LCCA has been widely studied over recent years, sustainability has not received enough attention in this regards. No comprehensive sustainability index has been developed to assess the road related projects over the life span in terms of economy and environment. This research aims to develop such an index using the analytical hierarchy process (AHP) to analyze the costs associated with road life cycle from a sustainable perspective to be able to select the best option from a list of alternatives for road related activities. Finally, this index is successfully validated through application of real case studies.

1. Introduction

Infrastructure systems and particularly transportation networks are playing a significant role in economy, environment, and society [1]. A number of cars in a transportation network is rapidly increasing; therefore, governments expand the network capacity. Environmental authorities concern about negative impacts of new transportation projects. In terms of economy, also, decision makers would not only think of initial cost. They carry out a process of assessment of all stages of a road from cradle to grave i.e., design, construction, implementation, operation, maintenance, and salvage values for an asset [2]. This process is called Life Cycle Assessment (LCA) [3]. Some researchers applied the LCA as a comprehensive method to evaluate environmental performance of an infrastructure [4, 5]. The LCA provides metrics that can be used to measure progress toward environmental sustainability [6].

The common method of assessing economic impacts of an asset is called LCCA. The LCCA is a complementary framework to LCA. which evaluates the monetary values of the processes and flows associated with a product or system [7]. The International Standard Organization has identified necessary modules of a comprehensive LCCA [8-10].

There is no consensus on using a unique number of modules for roads. Some researchers broke down the life cycle into ten modules while the others used four or five modules depending on the fact that whether they combined a few modules together or not e.g., combination of the maintenance module with the use phase [11]. The most common approach is to deploy a five-module LCCA including Materials, Construction, Maintenance and Rehabilitation (M&R), Usage, and End of Life (EOL) illustrated in Figure 1.

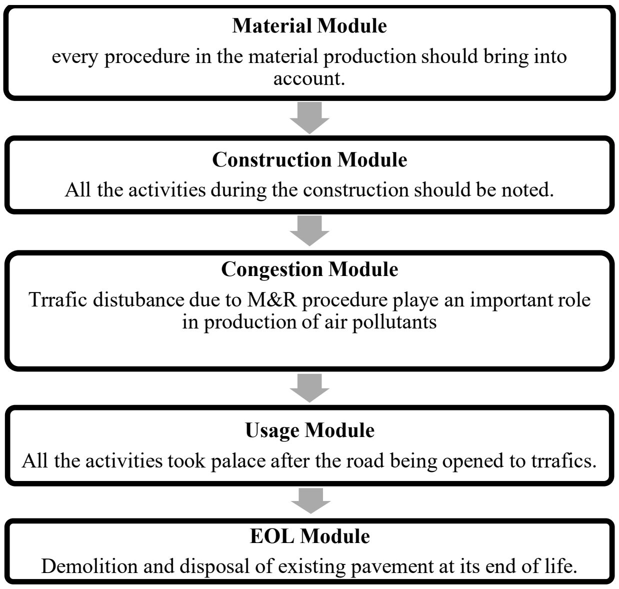

Figure 1. LCCA modules

* Corresponding Author:
E-mail address: agolroo@aut.ac.ir – Tel, (+98) 21-64544830 – Fax, (+98) 21-66963290

Received: 02 May 2017; Accepted: 20 June 2017

2. Research Background

The first step to conduct road LCCA is to select a series of above-mentioned modules to include in the analysis. Hakkinen and Makela [12] ignored the EOL module, while Horvath and Hendrickson [13] did not consider M&R modules. Roudebush [14] overlooked the use module, whereas Berthiaume and Bouchard [15] did not take into account construction and EOL modules. Mroueh et al. [11] ignored use and EOL modules, while Stripple [16] did not think of the EOL module. Park et al. [17] also ignored the use module. Trelor et al. applied a hybrid LCA method; however, they ignored the EOL [18].

Zapata and Gambatese [19] only brought materials and construction modules into consideration and compared the life cycle cost of asphalt concrete (AC) pavement and continuously reinforced concrete pavement (CRCP). Meil [20] disclosed one of the most comprehensive reports comparing the energy and global warming potential of AC and jointed plain concrete pavement (JPCP) in a project commissioned by the Cement Association of Canada. Bin Yu [21] developed an extensive data set for LCCA of hot mix asphalt (HMA), JPCP, and CRCP with design lives of 20 and 40 years. Most of the researchers have studied a few modules of LCCA (not all) such as Muga et al. [22], Huang et al. [23], and White et al. [24]; a comprehensive study is still lacking. Among all of these modules, costs associated with user and environment are the most difficult ones to evaluate in LCCA [25]. Each module has different levels of importance called weights in terms of sustainability.

One of the approaches to build a combined index using the above-mentioned modules is a weighted summation method. In this method, the costs associated with different modules are added up applying appropriate weights. To come up with proper weights, the AHP is one of the most useful methods introduced by Saaty [26].

The AHP method applies expert knowledge to obtain a set of weights showing the importance of each criterion. In this method, the decision hierarchy system includes the goal, criteria, sub-criteria, and a set of the alternatives. Pairwise comparison of criteria and sub-criteria is carried out. Having applied the results obtained from the comparisons, weights are assigned to the sub-criteria in the level immediately below and continued until the final priorities of the alternatives in the bottom most level are obtained.

In order to ensure that the process is valid, survey consistency should be checked [27]. An index which is applied to check the consistency is called consistency ratio (CR). In practice, a CR value less than 0.1 is acceptable [26]. In a study which suffers from lack of expertise, related experience, and for very abstract parameters, CR of up to 0.2 should be allowed [28]. Any higher value at any level indicates that the judgments warrant the reexamination.

To date, although as mentioned above, several research studies have been conducted on sustainability, developing a comprehensive combined index called a sustainability index for measuring the compatibility of a road construction project with sustainability criteria has received a little attention. This index can be applied to compare several alternatives for constructing a road according to the sustainability criteria.

3. Objective and Scope

This paper is to identify the most important criteria in a road construction project from sustainability perspective. The main objective of this study is to develop a sustainability index to be able to select the best alternative of a road construction project with regards to sustainability criteria. The scope of this research is to consider economic and environmental aspects of a road construction project among sustainability criteria. Moreover, in terms of environmental criterion, the gas emission data over the life cycle of a road is taken into account.

4. Research Methodology

After a detailed literature review, the first step was to indicate modules of LCCA for roads which should be studied according to sustainability criteria. The next step was to determine the weighting factors of each module using the AHP method. For this purpose, a survey was designed and domestic and international experts from both academia and industry who had worked on the subject of LCCA were invited to complete the survey. After analyzing the data obtained from the survey, the next step was to develop an index as a linear combination of weighting factors assigned to each module of road LCCA and to calculate the associated cost. The research methodology is illustrated in Figure 2.

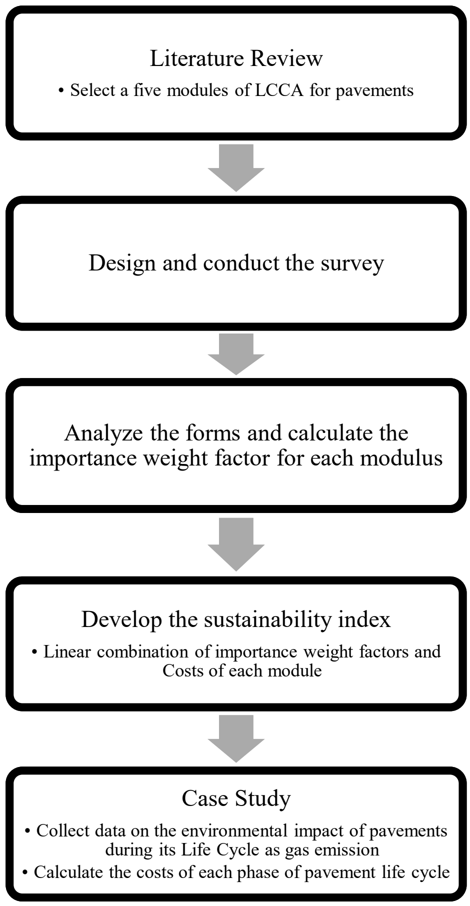

Figure 2. Research Methodology

4.1. Data Collection

4.1.1. Design a Survey

The survey was designed according to principles of the AHP method. The basic principle was to design a form to make pairwise comparisons between LCCA modules i.e., materials, construction, usage, maintenance, and EOL/salvage. It contained a scale that indicated how important or dominant one module was over another one with respect to sustainability criteria. In other words, the comparison was based on which module was more important with respect to the sustainability burden and how strong this importance was. The AHP form (including an instruction about how to fill the form) was designed and sent to experts by email along with a link to a web-based version of it due to saving time and cost and being environmentally friendly. A sample form is presented in appendix A.

4.1.2. Experts Selection

A group of experts at a total of ten employed in this survey were selected from Iran and other countries to be able to obtain both domestic and international opinions about the weights of sustainability modules. The experts had at least five years of related experience. They had a position at a university or worked at a well-established related company. The survey objectives and goals were explained to them and the method of completing the forms was elaborated. The experts had responded to the survey by filling the forms in less than a week.

4.2. Data Consistency

After filling out the forms by experts, CR was calculated for each comparison matrix (for every expert) to ensure that the experts consistently compare the LCCA modules through AHP. Table 1 represents the CR for each expert. As mentioned earlier, the threshold for CR was set to be 0.2 herein; therefore, all experts were consistent in comparing road LCCA modules.

Table 1. CR for each expert

Type	Domestic					International				
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10
CR	0.16	0.07	0.09	0.06	0.09	0.09	0.09	0.14	0.06	0.08

4.3. Developing sustainability indices

After analyzing the paired-wise comparison matrices using AHP, the weighting factors for each module for two types of experts/indices were calculated. The normalized values of weighting factors are as indicated in Table 2. The weighting factors followed almost the same pattern in both domestic and international categories. That is, the most important modules in the road LCCA was determined to be, in order of importance, the material, maintenance, usage/construction, and EOL.

Table 2. Normalized weighting factors for each module

Module	Domestic	International
Material	1	1
Construction	0.33	0.58
Maintenance	0.83	0.78
Usage	0.39	0.4
EOL	0.11	0.14

Having applied the normalized weighting factors (Table 2) into associated modules in terms of their costs, linear models were developed as follows which express the Sustainability Indices (SI).

$$SI_{Domestic} = 1X_1 + 0.33X_2 + 0.83X_3 + 0.39X_4 + 0.11X_5 \quad (1)$$

$$SI_{International} = 1X_1 + 0.58X_2 + 0.78X_3 + 0.40X_4 + 0.14X_5 \quad (2)$$

where

$SI_{Domestic}$= Domestic Sustainability Index

$SI_{International}$= International Sustainability Index

X_1= Total cost of the material module

X_2= Total cost of the construction module

X_3= Total cost of the maintenance module

X_4= Total cost of the usage module

X_5= Total cost of the EOL module

The conventional method applied to validate a model is to check its outcomes with ground truth and evaluate the errors i.e., the difference between the predicted values and actual measures. This method could not be utilized in this research due to the fact that there was no ground truth i.e., a standardized sustainability index for road LCCA with which the developed indices in this study were compared with. Therefore, a logical approach employed herein was to apply these indices to real case studies to evaluate them and ensure that the results make engineering sense.

Table 3. Emission produced applying the three alternatives

	Input output	Energy (GJ) Primary	Energy (GJ) Feedstock	CO_2 (tons)	CH_4 (kg)	N_2O (kg)	VOC (kg)	NO_x (kg)	CO (kg)	PM_{10} (kg)	SO_x (kg)
PCC	Ma	12709	NA	1219	659	4	111	2194	14118	3168	1158
	Co	285	NA	18	16	0.3	28	308	141	16	12
	Mn	11274	NA	759	-	-	877	-2908	-27414	116	1
	Ua	37083	NA	1863	-	-	3057	3376	73470	55	59
	EOL	100	NA	13	8	0.2	5	44	17	4	3
HMA	Ma	13958	39034	930	2247	1	205	1994	199	64	879
	Co	342	NA	73	21	0.4	37	412	183	33	16
	Mn	10792	NA	726	-	-	1103	-1625	-15291	67	3
	Ua	64688	NA	4964	-	-	4814	5343	115670	85	92
	EOL	143	NA	37	7	0.14	22	297	168	22	8
CSOL	Ma	9539	26668	636	1535	1	140	1362	136	44	60
	Co	192	NA	50	10	1	26	323	148	25	11
	Mn	8190	NA	551	-	-	1104	-1625	-15291	67	3
	Ua	56419	NA	4340	-	-	4767	5227	115215	86	92
	EOL	79	NA	21	4	0.1	12	165	93	12	5

Ma: Material, Co: Construction, Mn: Maintenance, Ua: Usage

5. Case Study

5.1. Major Rehabilitation

As the first case study, an old Portland Cement Concrete (PCC) pavement that was at the end of its service life was selected [21]. This road segment required major rehabilitation i.e., no maintenance action could be applied for further use. This pavement includes a PCC layer of 225 mm with 250 mm crushed aggregate as base course and subgrade. In each direction, the width of the inner paved shoulder, main lanes, and outsider paved shoulder are 1.2 m, 3.6×2 m, and 2.7 m, respectively. There is an annual average daily traffic flow (AADT) of 70,000, with 8% being truck that is growing at a growth rate of 4% per year. Three rehabilitation options frequently adopted are as follows:

- Remove and replace the 225 mm thick PCC pavement with 250 mm thick new PCC. Diamond grinding is frequently used to restore surface smoothness and reported to be viable for 16 years [21] and thus is performed every 16 years as a periodic rehabilitation strategy.
- Remove and replace the existing pavement with 225 mm thick HMA[1] (the HMA option). Use a mill-and-fill (remove 45 mm thick HMA surface and replace the same depth with new HMA) plan every 16 years as a periodic rehabilitation strategy [21].
- Crack, seat, and overlay (the CSOL option). Crack and seat the existing PCC pavement and then overlay with 125 mm thick HMA. Use the same mill-and-fill plan as the periodic rehabilitation strategy every 16 years [21].

The air pollutant emissions inventory of the case study is illustrated in Table 3. As shown in this table, the emissions of NOx and CO express negative values for the maintenance module due to the fact that, in one hand, the fleet speed decreases significantly during maintenance periods, on the other hand, the emission rates of NOx and CO are lower at low speeds than those at high speeds [29].

Table 4. Best estimate of unit cost of pollutants [21]

Air Pollutant	Best estimate as of 2010 dollar ($/tons)
CO_2	50
CH_4	625
N_2O	12341
VOC	1303
NO_x	5511
CO	354
PM_{10}	7851
SO_x	9695

The unit cost of each air pollutant is estimated using the study conducted by Sher [29] as presented in Table 4.

Having deployed the sustainability indices developed in this study, different alternatives were evaluated. Figure 3 illustrates that under similar circumstances, the CSOL alternative has the most desirable effect from sustainable perspective due to its lower sustainability index. The lower values show better environmental and economic conditions of the rehabilitation action. The other two alternatives approximately express the same influence on environment and economy due to their almost identical sustainability indices. The difference between the sustainability indices of CSOL and other rehabilitation actions expresses the advantage of CSOL over the others which makes engineering sense regarding the fact that CSOL consumes less energy and has less interference with environment

[1] Hot Mixture Asphalt

resulting in lower cost, while HMA has the most significant impact on the environment and economy.

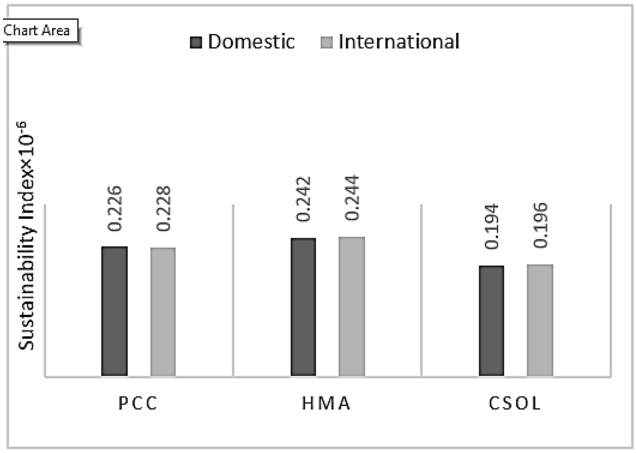

Figure 1. Sustainability indices for different rehabilitation actions

5.2. Road Construction

The second case study is related to several common road designs in the United States. The design factors are pavement type, traffic volume and design life. Two types of pavement i.e., rigid and flexible pavements and two design lives that are 20 and 40 years were considered. The environmental burdens of different pavement types including HMA, JPCP and CRCP were considered and presented in Tables 4 through 8 in appendix B. The HMA pavement was designed for 2800, 10000 and 38000 AADT for 20-year design life, while 5600, 10000 and 38000 AADT were considered for 40-year design life. For JPCP pavement 5600, 10000 and 38000 AADT were considered for both 20 and 40 years design lives. For CRCP pavement, 38000 AADT for both 20-year and 40-year design life were brought into calculation [21].

Two sustainability indices were calculated for all pavement design alternatives using both total and average annual costs caused by emission of gas pollutants. Figure 4 illustrates the sustainability index for the three abovementioned alternatives operating under 38000 AADT which were calculated using average annual cost. This figure shows that HMA and JPCP alternatives have less value for sustainability indices than CRCP; therefore, CRCP is more cost-effective and has less negative impacts on environment. It is also notable that both JPCP and HMA pavements have almost the same burden on environment.

Comparing Figures 4 and 5, it is observed that 40-year service life pavements have less environmental and economic burden according to the sustainability indices i.e., long-life pavements are a lot more compatible with sustainability criteria and more environmentally friendly. It is also concluded that domestic and international sustainability indices are almost identical which means that there is a sufficient consistency between models developed based on international and domestic experts knowledge.

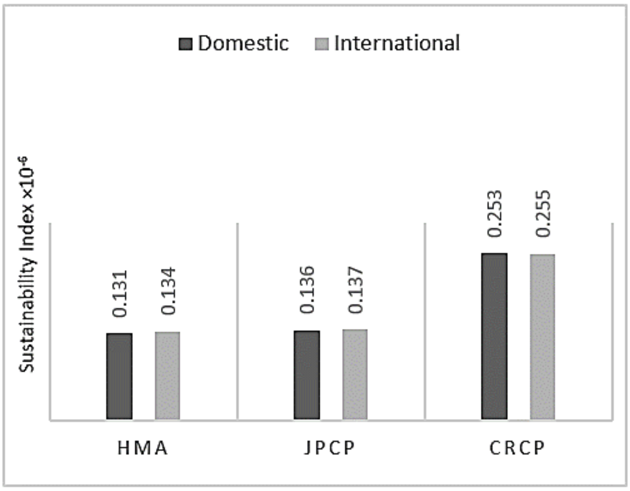

Figure 2. Sustainability Index for three different pavements with 38000 AADT and 20-year service life

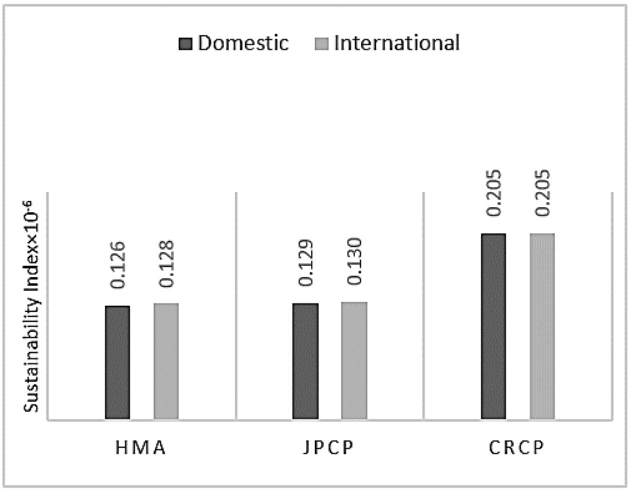

Figure 3. Sustainability Index for three different pavements with 38000 AADT and 40-year service life

Figure 6 shows the calculated sustainability indices for JPCP for different traffic volumes and service lives. This figure depicts that designing a pavement for a longer service life has better sustainable effects. It also illustrates that a road designed for a higher loading (more AADT) would have a less appropriate sustainability index. It seems logical since more loading requires stronger/thicker pavement structure which leads to more negative impacts on environment and be more costly.

In general, the validity of the sustainability indices was vividly proven due to the fact that the above-mentioned indices could sufficiently express the advantages of an alternative as compared to others which all would make engineering and logical sense. Having applied these indices, decision makers can confidently select the most sustainable alternative among proposed ones for a road construction/maintenance project.

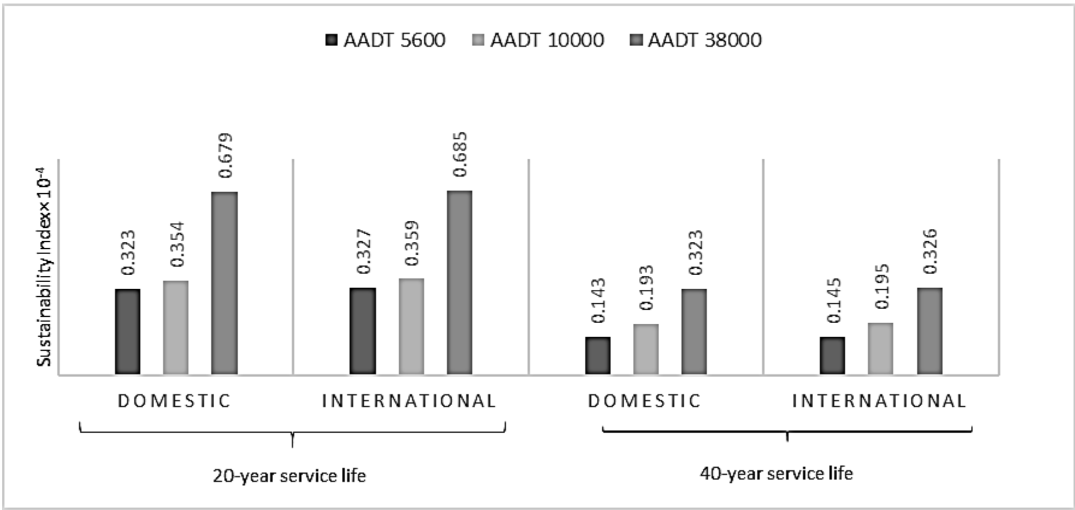

Figure 4. Sustainability index for JPCP pavement with three different yearly traffic and two different service lives calculated based on average annual cost

6. Conclusion

The impact of road construction on its life cycle on criteria such as environment, economy, and society always has been a controversial issue. A sustainability index which can measure the effect of such a project on these criteria is still lacking. The main aim of this study was to fill up this gap. First, the essential modules which should be considered in the life cycle cost analysis of a road project were determined including: material, construction, usage, maintenance, and salvage value. Then, sustainability indices were built based on the weighted summation approach. The weights for each module were derived through expert knowledge. The Analytical Hierarchy Process was employed to attain the weights. To validate the sustainability indices two real industrial projects/case studies were applied. The indices were calculated for road construction/maintenance alternatives in each case study. The indices could clearly assist to select the best alternative for road construction/maintenance according to sustainability concerns.

Appendix A

Sustainable Life Cycle Cost Analysis of Pavements Survey

Effecting air quality by emission of various gases is one of the major effects of a roadway project. And, the most important part of each road is its pavement. Life cycle of pavements can be divided into five phases: material preparation, construction, use, maintenance and salvage. Each phase can be studied individually from an environmental perspective especially emission of harmful gases.

The material preparation phase involves the processes needed to transform raw materials (e.g., aggregate, petroleum) into pavement materials (e.g., asphalt).The construction phase involves mostly the emissions from construction equipment and transportation of materials to the project site. The use phase includes activities that occur while the pavement is in place. Pavements interact with the environment through multiple pathways, including albedo, vehicle rolling resistance and lighting. The maintenance phase includes the maintenance, rehabilitation and reconstruction activities that occur during the life of a pavement. The maintenance phase usually involves its own materials, construction and use phases. Salvage phase, depending on current circumstances of pavement, can include demolition, disposal in a landfill, recycling processes and/or other activities.

The main purpose of this survey is to evaluate the level of importance of each phase compared to others by assigning weights with regards to its impacts on environment specially producing harmful gases. To fulfill this purpose you need to compare the importance of each phase to another (for instance the material phase compare to construction phase) by assigning a number between 1 and 9, according to instruction below (see Table A.1).

For instance, Table A.2 illustrates that material phase has a lower level of importance of 4 compare to construction phase while construction phase has a higher level of importance of 3 compare to maintenance phase.

Confidentiality Statement

The information provided by respondents will remain confidential and will be used for this research only. If you wish, we could send you the final outcomes of the survey.

Please complete Table A.3. Each row is related to pair comparison of two phases. Please start with the rows that you are more comfortable and confident about to be able to weigh them as a reference. Please check for consistency of your responses.

Table A.1. The fundamental scale of absolute numbers

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another, its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity I has one of the above non-zero numbers assigned to it when compared with activity j, then has the reciprocal value when compared with I	

Table A.2. Sample Table

First phase	Factor weighting score: More important than								Equal	Less important than								Second phase
Material	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	Construction
Construction	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	Maintenance

Table A.3. AHP form

First phase	Factor weighting score: More important than								Equal	Less important than								Second phase
Material	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	Construction
Material	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	Usage
Material	9	8	7	6	5	4	3	2 ●	1	9	8	7	6	5	4	3	2	Maintenance
Material	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	EOL
Construction	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	Usage
Construction	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	Maintenance
Construction	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	EOL
Usage	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	Maintenance

Usage	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	EOL
Maintenance	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	EOL

Appendix B

Table B.1. Life Cycle Inventory of HMA Designs (20-Year Designs)

Input-output		Energy (MJ)	CO2 (tonne)	CH4 (kg)	N O (kg)	VOC (kg)	NOx (kg)	CO (kg)	PM10 (kg)	SOx (kg)
2800 AADT- 20 years design	Material	6830530	517	830	0.8	76	1230	84	230	533
	Construction	244745	55	19	0.4	27	308	143	24	12
	Maintenance	120064	8	-	-	8	-34	-329	1	negligible
	Usage	2395364	163	-	-	186	204	4481	3	4
	EOL	66859	18	3.5	negligible	11	148	83.5	11	4
10000 AADT- 20 years design	Material	7728060	577	974	0.9	88	1358	97	234	589
	Construction	258973	57	20	0.4	29	319	147	25	13
	Maintenance	485529	33	-	-	34	-141	-1332	6	negligible
	Usage	8620080	586	-	-	663	734	15933	11	13
	EOL	71641	18.5	3.5	negligible	11	148.5	84	11	4
38000 AADT- 20 years design	Material	9892140	721	1323	1	120	1667	128	244	624
	Construction	388845	93	26	0.5	48	560	263	43	21
	Maintenance	4929327	331	-	-	423	-61	-4604	26	3
	Usage	31935342	2169	-	-	2496	2791	59663	43	47
	EOL	83469	19.5	4.5	0.1	11.5	149.5	84.5	110.5	4.5

Table B.2. Life Cycle Inventory of HMA Designs (40-Year Designs)

Input-output		Energy (MJ)	CO_2 (tonne)	CH4 (kg)	N O (kg)	VOC (kg)	NO_X (kg)	CO (kg)	PM_{10} (kg)	SO_X (kg)
5600 AADT- 40 years design	Material	7347573	552	912	0.9	83	1304	92	232	565
	Construction	258202	58	20	0.4	29	320	147	25	13
	Maintenance	136073	9	-	-	10	-40	-373	2	negligible
	Usage	2384251	162	-	-	185	203	4472	3	4
	EOL	71641	18.5	3.5	negligible	11	148.5	84	11	4
10000 AADT- 40 years design	Material	7945658	591	1009	1	92	1390	100	235	603
	Construction	280303	61	21	0.4	30	337	154	26	14
	Maintenance	628331	42	-	-	44	-176	-1721	7	0.3
	Usage	8903726	605	-	-	689	755	16657	12	13
	EOL	76331.5	19	4	0.1	11	149	84	11	4
38000 AADT- 40 years design	Material	9842382	717	1314	1	120	1660	127	244	723
	Construction	332807	66	24	0.5	33	359	163	28	15
	Maintenance	4300649	107	-	-	378	-718	-5701	30	2
	Usage	32299287	2194	-	-	2477	2766	59245	42	47
	EOL	88610	20	5	0.1	11.5	150	84.5	11	4.5

Table B.3. Life Cycle Inventory of JPCP Designs (20-Year Designs)

Input-output		Energy (MJ)	CO2 (tonne)	CH4 (kg)	N O (kg)	VOC (kg)	NOx (kg)	CO (kg)	PM10 (kg)	SOx (kg)
5600 AADT- 20 years design	Material	6396354	643	122	0.7	37	1504	2730	1313	778
	Construction	211512	34	20	0.4	16	144	67	12	8
	Maintenance	143945	10	-	-	10	-42	-395	2	negligible
	Usage	1895117	129	-	-	161	177	3862	3	3
	EOL	40575	3	4	negligible	1	4	2	0.5	0.8
10000 AADT- 20 years design	Material	5614896	576	120	0.7	33	1327	2646	1173	640
	Construction	219731	34	18	0.3	18	174	88	14	8
	Maintenance	571210	38	-	-	40	-170	-1614	7	0.1
	Usage	7746577	526	-	-	649	705	15754	12	1
	EOL	45331	3	4	negligible	1	4	4	0.5	0.9
38000	Material	7030110	654	123	0.9	38	1594	2742	1317	738

AADT- 20 years design	Construction	256524	38	-	-	20	194	95	16	9
	Maintenance	4540228	305			390	-687	-5159	31	2
	Usage	30556851	2076	-	-	2563	2795	62064	45	50
	EOL	54879	4	5	negligible	2	5	2	0.6	1

Table B.4. Life Cycle Inventory of JPCP Designs (40-Year Designs)

Input-output		Energy (MJ)	CO_2 (tonne)	CH_4 (kg)	N O (kg)	VOC (kg)	NO_X (kg)	CO (kg)	PM_{10} (kg)	SO_X (kg)
5600	Material	6050438	570	119	0.9	32	1372	2636	1141	623
	Construction	211996	26	17	negligible	12	96	40	8	6
	Maintenance	151942	10	-	-	11	-44	-417	2	negligible
	Usage	2011837	137	-	-	170	185	4114	3	3
	EOL	42962	3	4	negligible	1	4	2	0.4	0.8
10000	Material	6834120	637	122	0.9	37	1549	2720	1282	715
	Construction	235775	30	18	negligible	14	115	48	10	7
	Maintenance	657496	44	-	-	46	-191	-1802	8	negligible
	Usage	7822931	531	-	-	657	707	16000	12	13
	EOL	52492	4	4	negligible	1	5	2	0.5	0.8
38000	Material	7617663	704	124	0.9	41	172	2805	1423	807
	Construction	259539	34	19	negligible	15	134	55	11	6
	Maintenance	2930309	197	-	-	206	-852	-8041	34	0.2
	Usage	30815249	2093	-	-	2582	2772	62996	48	51
	EOL	62039	5	5	negligible	2	6	3	0.6	1

Table B.5. Life Cycle Inventory of CRCP Designs

Input-output		Energy (MJ)	CO_2 (tonne)	CH_4 (kg)	N O (kg)	VOC (kg)	NO_X (kg)	CO (kg)	PM_{10} (kg)	SO_X (kg)
38000 AADT- 20 years design	Material	13117777	1320	815	5	112	2218	173124	3375	812
	Construction	225642	28	17	negligible	13	120	58	10	7
	Maintenance	7439908	464	-	-	612	-1536	-13123	65	2
	Usage	24756721	1682	-	-	2109	2344	50474	38	40
	EOL	47719	2	4	negligible	1	4	2	0.5	0.9
38000 AADT- 40 years design	Material	13583220	1381	928	6	122	2198	19670	3619	761
	Construction	247657	32	19	negligible	14	124	51	10	8
	Maintenance	6077678	409	-	-	427	-1768	-16678	70	0.3
	Usage	26284833	1785	-	-	2234	2470	53610	40	43
	EOL	57266	4	5	0.1	2	5	3	0.6	1

References

[1] N.J. Santero, Life-cycle assessment of pavements, Part I: Critical review. Resources, Conservation and Recycling 55 (2011) 801–809.

[2] D.J. Cass, Estimating greenhouse gas emissions of highway construction and rehabilitation to support pavement life cycle assessment, Michigan Technological University, 2011.

[3] M.A. Surahyo, Environmental and Social Cost Modeling of Highway Projects, University of Toronto, 2005.

[4] G.A. Norris, Integrating life cycle cost analysis and LCA, The International Journal of Life Cycle Assessment 6 (2001) 118–120.

[5] O. Ortiz, Sustainability in the construction industry: A review of recent developments based on LCA, Construction and Building Materials 23 (2009) 28–39.

[6] H. Zhang, Sustainable pavement asset management based on life cycle models and optimization methods, The University of Michigan, 2009.

[7] G.A. Keoleian, D.V. Spitzley, Life cycle based sustainability metrics, Sustainability Science and Engineering: Defining Principles 1 (2006) 127–159.

[8] ISO Environmental Management: Life Cycle Assessment: Principles and Framework, International Organization for Standardization, 1997.

[9] ISO Environmental Management: Life Cycle Assessment: Goal and Scope Definition and Inventory Analysis: ISO 14041, International Organization for Standardization, 1998.

[10] ISO Environmental Management: Life Cycle Assessment: Life Cycle Impact Assessment: ISO 14042, International Organization for Standardization, 2000.

[11] U.M. Mroueh, Life Cycle Assessment Of Road Construction, Final report to Finnish national road administration, 2000.

[12] T. Häkkinen, K. Mäkelä, Environmental Impact of Concrete and Asphalt Pavements, in Environmental adaption of concrete, Research Notes 1752, Technical Research Center of Finland, 1996.

[13] A. Horvath, C. Hendrickson, Comparison of Environmental Implications of Asphalt and Steel-Reinforced Concrete Pavements, Transportation Research Record: Journal of the Transportation Research Board 1626 (1998) 105–113.

[14] W. Roudebush, Environmental value engineering assessment of concrete and asphalt pavement, Portland Cement Association. PCA R&D Serial (2088a), 1999.

[15] R. Berthiaume, C. Bouchard, Exergy analysis of the environmental impact of paving material manufacture, Transactions of the Canadian Society for Mechanical Engineering 23(1) (1999) 187–196.

[16] H. Stripple, Life cycle assessment of road, A pilot study for inventory analysis. 2nd revised Edition, Report from the IVL Swedish Environmental Research Institute 96, 2001.

[17] K. Park, Quantitative assessment of environmental impacts on life cycle of highways, Journal of Construction Engineering and Management 129 (2003) 25–31.
[18] G.J. Treloar, Hybrid life-cycle inventory for road construction and use, Journal of Construction Engineering and Management 130 (2004) 43–49.
[19] P. Zapata, J.A. Gambatese, Energy consumption of asphalt and reinforced concrete pavement materials and construction, Journal of Infrastructure Systems 11 (2005) 9–20.
[20] J. Meil, A life cycle perspective on concrete and asphalt roadways: embodied primary energy and global warming potential, Athena Research Institute (2006).
[21] B. Yu, Environmental Implications of Pavements: A Life Cycle View, Ann Arbor, University of South Florida, 3557321: 236 , 2013.
[22] H.E. Muga, An integrated assessment of continuously reinforced and jointed plane concrete pavements, Journal of Engineering, Design and Technology 7 (2009) 81–98.
[23] Y. Huang, A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation, Transportation Research Part D: Transport and Environment 14 (2009)197–204.
[24] P. White, Modeling climate change impacts of pavement production and construction, Resources, Conservation and Recycling 54 (2010) 776–782.
[25] T. C. C. R. PIARC, Whole-Life Costing of Roads - Concrete Roads, PIARC, 2000.
[26] T.L. Saaty, How to make a decision: the analytic hierarchy process, European Journal of Operational Research 48 (1990) 9–26.
[27] T.L. Saaty,. Decision making with the analytic hierarchy process, International Journal of Services Sciences 1 (2008) 83–98.
[28] L.G. Vargas,. An overview of the analytic hierarchy process and its applications, European Journal of Operational Research 48 (1990) 2–8.
[29] E. Sher, Handbook of air pollution from internal combustion engines: pollutant formation and control. Academic Press, 1998.