Functional Unit Choice for Comparative Pavement LCA Involving Use-Stage with Pavement Roughness Uncertainty Quantification (UQ)

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ABSTRACT: An analysis of the use-stage for pavement life-cycle assessment (LCA) is presented within a framework of an LCA tool developed for Illinois Tollway. Methodological choices that can significantly affect LCA results were evaluated in this study. The share of the use-stage in a comprehensive pavement LCA framework was evaluated with all life-cycle stages including materials, construction, use, maintenance, and end of life. The scope of the use-stage includes albedo, carbonation, and rolling resistance (including pavement roughness and texture components). Uncertainty of the pavement roughness and its effect on the results are investigated using Monte Carlo sampling technique. A discussion on the choice of functional unit and its effect in comparative LCA is presented and an appropriate functional unit is suggested. Four projects were selected as case studies to demonstrate the capabilities of the tool and proposed framework. A multi-point environmental performance evaluation was performed using four environmental indicators for comprehensive interpretation of results. The effect of each stage of LCA was evaluated with emphasis on the results of the use-stage. Additional fuel consumption and emissions, resulting from roughness and texture, constituted the largest share of use-stage impacts while the effect of carbonation was limited. As traffic reduced and the share of the materials and construction stage increased, the share of the use-stage could be decreased to 50% levels.

1 INTRODUCTION

Life-cycle assessment (LCA) is one of the sustainability measurement tools used to quantify life-cycle environmental impacts of a product. Recently, pavement LCA applications have been increased with an emphasis on sustainability for the construction industry aiming at reducing carbon footprint of pavements. In order to accurately characterize the environmental impact of pavements, Federal Highway Administration (FHWA) recently published pavement LCA framework following the International Standards Organization (ISO) 14040 and 14044 standards (Van Dam et al; 2015; Harvey et el., 2016; ISO, 2006).

There is certainly a need for an easy-to-use, and yet reliable, model capturing the nature of pavement–environment interaction that can be incorporated in pavement LCAs for the use of LCA experts as well as LCA users in agencies and industry. This can facilitate implementation of LCA with its most needed components related to the use-stage and improve sustainability of pavement systems. In general, some studies ignore the use-stage component completely (i.e., texture, albedo, and carbonation) or simplify it to a degree that renders the need to use other software platforms unnecessary (Wang et al., 2012). Finally, most previous studies focused on energy consumption and/or GHG only as part of the impact characterization and the sole outcome of the LCA (Wang et al., 2014, Shakiba et al., 2016). However, a comprehensive pavement LCA, similar to other products and services, should ultimately include environmental impact categories other than energy and GHG as outlined by characterization methods such as TRACI (Bare, 2011), CML (Guinée et al., 2002). This is provided by a multi-point environmental assessment opportunity, rather than relying on only energy and GHG.

Common challenges in performing pavement LCA were reviewed and discussed in details by Santero et al. (2011a, b) through a comprehensive review of existing pavement LCA literature and modeling tools as of 2010. Data and modeling gaps were identified in pavement LCAs and in particular for the use-stage, feedstock energy of bitumen, impact of traffic delay, maintenance phase, end-of-life stage, and inconsistencies for various methodological choices were summarized. Inyim et al. (2016) and AzariJafari et al. (2016) reviewed the current literature and pointed out similar gaps in more recent studies.

One of the challenges in performing comparative LCA is the choice of functional unit (FU). The functional unit is a unit of measurement of system components to which inputs and outputs of LCA are normalized. According to ISO 14044:2006, functional unit is "quantified performance of a product system for use a reference unit". ISO standards recommends to choose functional consistent with the goal and scope of the study where primary function and performance characteristics of the product are specified. The purpose of the functional unit is to quantify the services delivered by the product system. Therefore, the functional unit shall declare the relevant functions of the product with some performance characteristics. The flaws in some of the commonly used FUs are discussed in the following sections and a proper FU is proposed.

While comprehensive methodological choices are needed to implement the pavement LCA, there are many uncertainty sources associated with pavement LCA. Some of these uncertainties include, but are not limited to: input variability, human errors, source credibility, and parameter and model uncertainty. Studies have focused on the uncertainty analysis of pavement LCA (Noshadravan et al., 2013; Gregory et al., 2016). Uncertainty quantification (UQ) methods are mathematical methods that help identify, propagate, quantify, and interpret the uncertainties in the system. Each stage of the pavement LCA may need different handling of uncertainty depending on the type of the source. Quantifying uncertainties would ultimately help understand the variations in the pavement LCA analysis and to what extent these variations affect the reliability of the outcome. Moreover, this would let decision-makers consider ranges of outcomes rather than deterministic values, henceforth, helping in informative decision-making with better understood consequences.

The main goal of this paper is to present the essential components needed to perform a complete LCA (cradle-to-grave analysis) to compare pavement systems with varying designs, and traffic characteristics. The main components targeted in this study include selection of an appropriate functional unit and uncertainty quantification. Uncertainty quantification of the use stage is performed by studying the variability in the pavement roughness. Both of these components are presented with illustrative examples through case studies.

2 METHODOLOGICAL CHOICES AND LIFE-CYCLE INVENTORY ANALYSIS

2.1 *Goal of the Study*

The goal of the study is to develop an LCA tool and framework for the Illinois Tollway in order to perform a comparative LCA between projects constructed in the past and planned for future. The intended application is to evaluate the progress toward the agency's sustainability goal from environmental performance perspective by reporting and comparing environmental performance of past and present projects, and pavement type and design selection using environmental performance in addition to cost and performance.

2.2 *System Boundary*

A system boundary in an LCA defines the processes and life-cycle stages included. The system boundary for the current study includes all stages of the pavement LCA. Material acquisition and production, construction, maintenance, use-stage, and end-of-life stages are included. Rolling resistance, carbonation, and albedo components are included in the use-stage. Upstream (data from supply chain such as electricity production, extraction of crude oil and transportation, etc.) and downstream processes (typically processes starts with material stage) are included.

2.3 *Choice of Functional Unit for LCA Involving the Use-stage*

In comparative LCA, a consistent functional unit (FU) must be chosen in order to compare two or more pavement systems. The functional unit for pavements should represent physical dimensions and pavement performance. Performance requirements can include design life, traffic level, subgrade type, and pavement condition and should be reported or explicitly included in the functional unit. Typically, a functional unit for pavements is defined as "*entire project dimensions or lane-mile through a specified lifetime fulfilling specifications and performance requirements*". This type of functions unit only reporting the physical dimensions of the project may not be sufficient for comparative LCAs where pavement performances are different.

Therefore, the functional unit should effectively reflect the characteristics of the pavement section under LCA study. Different functional units have been used in literature for pavement LCA studies. Three categories can be identified:

- Physical: Physical or geometrical functional units account for dimensions of the project such as, project-length (mile or kilometer), lane-length (lane-mile or kilometer), volume (material), etc. This is the most commonly used functional unit in the literature. Depending on the goal of the study, this functional unit can be appropriate to use. The following scenarios are among the typical examples: reporting total GHG emissions or energy consumption attributed to a pavement system or network of pavements, interpretation of life-cycle stage contribution, etc.
- Structural or performance-based: Structural or performance-related functional units account for the condition of pavement or factors that affect performance such as, traffic (ADT/AADT), load (Equivalent single axle load (ESAL)), and performance-lane-length. For example, per pavement serviceability rating (PCR) per lane per mile (Santero & Horvath, 2011a). This type of functional units can be used for comparative evaluation of two or more pavement systems.
- Annualized: The results obtained from geometry-related functional units are normalized by the analysis period. This type of functional unit is commonly used for comparative LCAs to evaluate sustainability improvement between two or more types of pavements. For example, functional unit becomes lane-mile-year.

For a fair comparison of projects, FU should not penalize the projects by their total length, number of lanes, analysis period and traffic level. Instead, it should account for the performance. This means one would normalize LCA results by dimensions of the project, analysis period and traffic and directly account for the performance. In this regard, the categories in the above-mentioned list should not be considered as proper choices.

It should be noted that structural FUs are usually necessary when the goal is to conduct comparative LCAs for projects with different design characteristics e.g. different traffic or analysis period. These type of comparisons are necessary for benchmarking studies where current projects are meant to be compared to some baseline projects from the past while the design parameters can be different. While a true FU can never be sought for these types of projects, due to inherent differences in all aspects of the comparison, we argue that if the pavement performance is considered in the use-stage calculations, it would be unnecessary to explicitly include performance in the FU. Instead, FU should account for the missing component i.e. traffic or ESAL, along with physical dimensions of the project to avoid penalizing projects serving higher traffic levels.

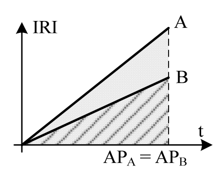
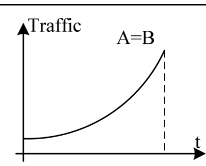
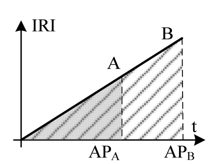
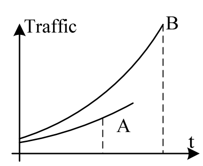
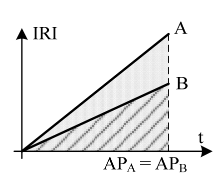
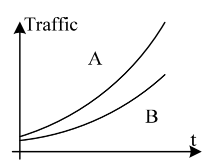
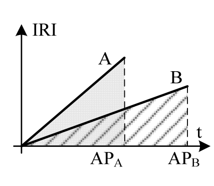
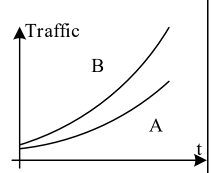
It is clear that regardless of the chosen methodology, use-stage components somehow account for the performance e.g. through roughness, texture or deflection indicators, albedo change over time, or carbonation parameters for concrete sections. Meaning, poor performing section will result in more impacts. Therefore, this study proposes a new functional unit that accounts for traffic as well as physical characteristics of the projects being compared. Vehicle-length traveled (VLT) in terms of vehicle-miles-traveled (VMT) or vehicle-kilometer-traveled (VKT) is proposed as a an alternative choice of functional unit choice when the goal of the study is to compare two pavements with design features common for benchmarking applications.

Although seem trivial, we expand the discussion here to explore flaws in the physical FUs as well as show sufficiency of the proposed FU when dealing with comparative LCAs involving use-stage.

Table 1 presents a comparison of some of the commonly used functional units with their potential consequences on the comparison of two hypothetical pavement systems. Varying scenarios are presented with the expected use-stage impact when three types of functional units are used. Performance of pavement is characterized by IRI and traffic level also affecting directly the use-stage impacts through excess vehicle fuel consumption. The higher the area under the IRI or traffic growth curves, the higher the use-stage impact is. When only physical units (i.e. lane-mile) or annualized functional unit (lane-mile-year) are used, in general longer living pavements and pavements serving for higher traffic volumes can be penalized.

As shown with the hypothetical examples, VLT choice results in more consistent comparison of two pavements favoring good performing sections serving for higher traffic volumes. Since VLT accounts for the “usage” of the system by users, it is applicable to all LCA stages when the system boundary includes use stage. Essentially, VLT is a proper choice if any aspect of the LCA include time variable in it. This is because a pavement section is designed to serve users over time usually represented by ADT/AADT. Thus, a proper FU should account for traffic in a similar way that should account for time and dimensions of the project.

Table 1. Functional unit scenarios and consequences for comparative LCAs.

Scenario Description for Comparison	**Performance (in terms of IRI)**	**Traffic**	**Functional Unit Choice and Consequences on Use-stage Impact**
Alternative pavement trials for the same traffic with same design lives. Different expected performance (poor performance for A) with same analysis period.			LM: A > B LMY: A > B VMT: A > B *Consistent results when analysis period is the same.*
Different designs with different design lives accounting for traffic volume differences. Similar expected performance within the analysis period (shorter life for pavement A).			LM: B > A LMY: most likely B > A VMT: most likely A = B *LM and LMY will penalize longer living pavement. Results depend on change in AP and differences in performance and traffic.*
Arbitrary selection from network with different performance and traffic. Same or different design lives. Assume A is the poor performing with higher traffic and same analysis period.			LM: A > B LMY: A > B VMT: most likely A > B *- VMT will favor better performing pavement B if traffic volume is not too low. - If traffic volume is too low, indication of overdesign.*
Arbitrary selection from network with different performance and traffic. Same or different design lives. Assume A is the poor performing with different traffic.			Total: can vary. LM: can vary. LMY: can vary. VMT: most likely A > B *- VMT will favor better performing pavement B.* *- Under higher traffic conditions LM and LMY may penalize pavement B.*

AP = analysis period

LM: lane-mile

LMY: lane-mile-year

VMT: vehicle-mile-travelled

Analysis period is another critical choice for a fair comparison of pavement systems. Analysis period should be chosen to capture initial pavement and through the life of at least the next subsequent major rehabilitation treatment or next full reconstruction (Van Dam et al., 2015). The comparisons presented in Table 1 applies to the cases where analysis period is extended through the entire life-cycle of pavements till the end-of-life or subsequent major treatments (IRI performance curves are shown with linear curves for simplicity). In this study, analysis period is chosen as the time period from initial construction to the reconstruction.

2.4 *Material, Construction, Maintenance, and End-of-Life Stages*

Inventory data regarding the operation of equipment, production of materials, transportation of materials, and plant operations for pavement mixtures were considered using various primary and secondary data sources (e.g., literature, government and industry reports, commercial software and simulators, surveys). A life-cycle inventory database was developed combining operational or process activity data collected with processes available in commercial software and databases such as SimaPro and US-Ecoinvent. The inventory database was compiled in terms of pay items compatible with the agency's procurement procedures. A cost-based cut-off criteria was used including pavement pay items that contribute to the top 95% or 0.5% of the total pavement cost. In addition, a cut-off allocation was applied for recycled materials, by-products, and waste products where only processes directly related to the post-processing or preparation of secondary materials were considered. A similar cut-off allocation rule was used for the end-of-life (EOL) stage, where the processing of any material destined to be recycled or reused after the current pavement system ends is cut-off and attributed to the future pavement system. Feedstock energy of bituminous material was also considered. Detailed information on material and construction, maintenance, and end-of-life stages can be found elsewhere (Yang et al, 2016, Kang et al., 2014).

2.5 *Use-stage*

Use-stage components include, rolling resistance, albedo, carbonation, lighting and leachate. Depending on the availability of data/models, and the importance of the components on overall impacts, the system boundary may include one or more of the use-stage components. The system boundary in this study includes all modules of the use-stage, except structural rolling resistance (deflection-related), leachate, and lighting. The modules were selected based on the availability of the methods and their significance on overall LCA results. The following sub-sections provide methodological choices for current study.

2.5.1 *Albedo*

Albedo is the main controlling property defining the measure of the ability of a surface to reflect solar radiation. It ranges from 0 (perfectly non-reflective) to 1 (perfectly reflective material). Albedo directly affects the radiative forcing, a measure of the balance of incoming and outgoing energy in the earth-atmosphere system. The effect of albedo can be used to quantify the heat island effect and radiative forcing using the following equation from the FHWA LCA framework (Harvey, et al., 2016).

$$m_{CO2} = \sum_{n=1}^{N} 100 * \left(\alpha_{new}^{n} - \alpha_{ref}\right) * \left(f_{RF}\right) * A \tag{1}$$

where,

m_{CO2} = total CO2 offset or gain in kg over the analysis period

α_{new}^{n} = the mean albedo value of original pavement construction and subsequent treatments as an average value of initial albedo right after construction and final albedo before the next treatment

α_{ref} = reference albedo value that can be taken as the albedo of old pavement surface replaced by new construction or network average albedo

f_{RF} = CO2 offset per an increase of 0.01 rise in albedo in kg CO2 m-2 (between 2.55 and 4.90 kg CO2 m-2)

A = total surface area of new pavement construction in m2

N = total number of treatment activities replacing surface layers during the analysis period

According to literature, the following albedo (α) ranges for new and weathered surfaces were used (Kaloush et al., 2008): 0.05 (new) and 0.15 (weathered) with an average of 0.1 for asphalt and 0.4 (new) and 0.2 (weathered) (average of 0.3) for Portland cement concrete surfaces, respectively. The first value is for the new surface, and the second value is for the weathered surface.

2.5.2 *Carbonation*

Carbonation is the process whereby carbon dioxide is reabsorbed and stored in concrete to form a bond with calcium oxide and calcium hydroxide, resulting from the calcination process during cement manufacturing. This process takes place only in concrete pavements. The majority of pavement LCAs that consider carbonation follow a model included in the works by Pommer and Pade (2006) and Lagerblad (2005). The model includes several factors that control absorption over time and uses a simplification of Fick's second law of diffusion as presented by Santero & Horvath (2009).

Following the work by Lagerblad (2005), the following equation was used to calculate carbon dioxide uptake during the life cycle of concrete:

$$CO_2(kg) = k \times t^{0.5} \times c \times CaO \times r \times A \times M \tag{2}$$

where,

k = 1.25 × CF_lime × CF_FlyAsh (base k-value based on CEM type I half burried-half exposed). If CEM type II is used multiply the base of the equation (1.25) by 1.10 or (1.25×1.10)

CF_lime = 1.05 for 10% limestone, and 1.10 for 20% limestone

CF_FlyAsh = 1.05 for 10% fly ash, 1.10 for 20% fly ash, and 1.20 for 40% fly ash

c = Quantity of cement in mix (kg/m3)

CaO = 0.65, the amount of CaO content in Portland cement

r = 0.75, the proportion of calcium oxide that can be carbonated

A = the exposed surface area of concrete (m^3)

M = 0.79, the chemical molar fraction (CO_2/CaO)

t = exposed carbonation time (years)

2.5.3 *Rolling Resistance (RR)*

It has been estimated that approximately 20% of transportation-related consumption is due to rolling resistance (IEA, 2005). Rolling resistance is defined in ISO 28580:2009 as the loss of energy or the energy dissipated per unit of distance traveled (ISO, 2009). Pavement-related factors that affect RR include unevenness (also called roughness), pavement structure (deflection based), and texture.

A recent study developed a model called the RSI (Roughness-Speed Impact) model to relate energy and emissions to pavement roughness and vehicle operating conditions using vehicle specific power model (Ziyadi et al., 2016):

RSI model for vehicle energy consumption:

$$\Delta\hat{E}(v, \Delta IRI) = (k_a + k_c \cdot v^2) \times \Delta IRI \tag{3}$$

where,

$\Delta\hat{E}$= Estimated additional energy consumption per vehicle distance (kJ/mile)

v = Average speed (mph)

k_a, k_c = model coefficients defined for each type of vehicle

ΔIRI = incremental changes in IRI between two consecutive analysis steps

This model uses a series of incremental tables (Ziyadi et al., 2016) to estimate the TRACI impact.

The main inputs of the RSI models are IRI and traffic composition and speed. Since LCA covers a long span of time, it is important to know how these inputs change over time. IRI increases over time as pavement deteriorates and decreases (*improves*) upon application of any maintenance and rehabilitation (M&R) project. IRI progression curves and drop models were developed for the pavements in the Tollway network using historic data.

A calibrated HDM4 model (Chatti & Zaabar, 2012) is used to calculate the additional fuel consumption due to pavement texture for trucks only. Global warming potential (GWP) is calculated based on energy conversion. The following linear relationship is used to interpolate the percent change in fuel consumption due to 1 mm increase in mean profile depth (MPD) and speed:

$$\delta E_{texture}(\%) = 0.02 - 2.5 \times 10^{-4} \times (v - 35) \tag{5}$$

where,

$\delta E_{texture}$ = percent change in fuel due to 1 mm increase in MPD

v = speed (mph)

Texture progression models were developed using literature model (Chatti & Zaabar, 2012) and calibrated with historic data from the Tollway network.

3 UNCERTAINTY QUANTIFICATION (UQ)

Pavement roughness measured and reported in terms of IRI is one of the main inputs to the pavement LCA that has significant effect on the results, yet it is prone to many uncertainties. Human and measurement errors are among those. Assuming there is a true value of IRI every year for each pavement section, variations in data can be modeled as normal probability distribution. Using this concept, uncertainties in the IRI were propagated throughout the LCA calculation. Monte Carlo sampling technique is used for this purpose. Statistical parameters of the distributions including mean and standard deviations for this study were collected from historical data and calculated using similar pavement types.

4 IMPACT ASSESSMENT

Four environmental indicators were selected to assess the impacts including single score (SS), total primary energy (TPE), global warming potential (GWP) and primary energy as fuel (PEF). Results from different TRACI impact categories were normalized (Lautier et al, 2010) and weighted (Bare et al., 2006) based on National Institute of Standards and Technology (NIST) to a single score to simplify for external use. Care should be taken when interpreting SS because it is a highly simplified indicator of multiple complex impact categories. TPE includes all energy embodied as fuel (e.g., diesel, natural gas) and material (e.g., petroleum products such as plastics, asphalt binder), whereas PEF only includes the energy embodied as fuel.

5 CASE STUDIES

Four pavement-widening projects were selected for analysis using the developed LCA tool and methodologies presented in this paper. Projects were selected from the Illinois Toll highway (Tollway) network located in the Chicago metropolitan area. Two past (2008 and before) and two current (2012 and after) widening projects were selected from a total of 14 historical and current projects representing a wide range of cases. Table 2 summarizes these projects and presents relevant information. All projects are jointed plain concrete sections (JPCP). Traffic ranges from low AADT of 19,240 for to a high AADT of 148,200. The functional unit proposed in this study (VMT) was used to interpret the results from these projects.

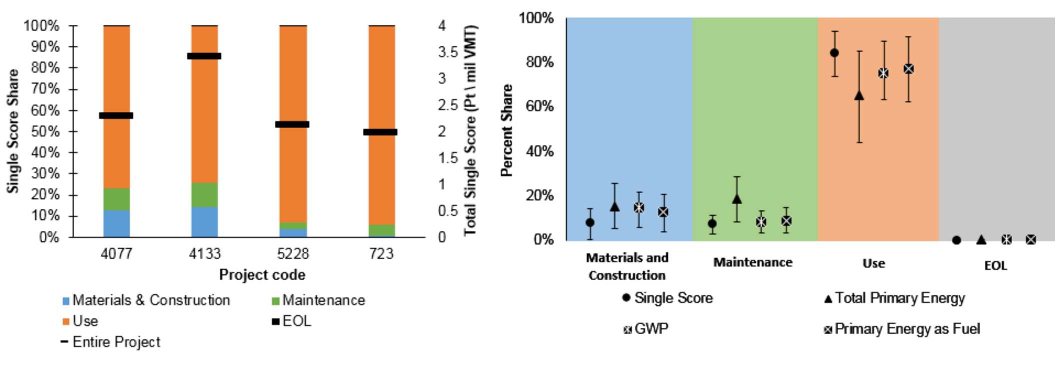
Table 2. Case Study Project Information

Toll Road	Year	Project Code	Milepost	Length (mi)	Analysis Period (yr)	AADT; % Truck	Description
Jane Addams Memorial I-90/I-39/ US 51	2012-2013	4077	49.7 to 53.6	3.9	62 yrs; 3 overlays	28,460 EB; 13.3%	Roadway widening (3 lanes 12-inch JPCP) and reconstruction
	2014	4133	24.9 to 33.5	8.6	62 yrs; 3 overlays	19,240 WB; 20.3%	Roadway widening (3 lanes 11.25-inch JPCP) and reconstruction
Tri-State I-94/I-294/ I-80	2007-2008	5228	15.84 to 13.24	2.6	62 yrs; 3 overlays	148,200 SB 14.6%	Roadway widening and reconstruction (with 12-inch JPCP) from 3 to 4 lanes
Ronald Reagan Memorial I-88	1999	723	133.7 to 138.8	5.1	44 yrs; 2 overlays	76,680 EB; 80,670 WB; 9.8%	Roadway widening and reconstruction to 3 (12-inch JPCP) lanes

6 RESULTS AND ANALYSIS

Four LCA projects were analyzed using the Illinois Tollway Roadway/Roadside tool and environmental impacts were calculated according to the system boundary as described above. The purpose of the analysis is to examine the ranges and share of each influential factor and perform a project-to-project comparison to evaluate environmental sustainability improvements over the years. Figure 1-a shows the share of each stage for each project per functional unit. The use-stage share is almost 50 to 90% of environmental impacts in terms of single score (SS), total primary energy (TPE), global warming potential (GWP), and primary energy as fuel (PEF) (Figure 1-b). The figure presents a significant range of values each stage contribute to the total environmental performance calculated from four projects. The error bars on Figure 1-b show the range of values based on the four projects.

It should be noted that new projects have the lowest contribution from use-stage among all projects. This is partly because the new projects carry lower traffic. In addition, investigating the processes involved in the LCA stages reveals that new projects involve more material and construction processes and, therefore, the material and construction and maintenance stages account for around 30% of total impacts alone.



(a) Single Score (b) All Indicators

Figure 1 Environmental impact breakdown of LCA case studies for (a) single score and (b) all indicators.

The breakdown of processes contributing to the use-stage is shown in Table 3. The table shows a comparison of the four projects with their corresponding total impacts and impacts per functional unit. First, it is clearly shown that a significant portion of GWP impacts are associated with the additional fuel consumption of passenger vehicles due to roughness. The total absolute impacts for the new projects (4077 and 4133) with relatively lower traffic are smaller than the others.

Total absolute impacts reflected into the impacts calculated per the functional unit chosen with physical characteristics (lane-mile) and annualized lane-mile. These two functional units resulted in higher impacts for the two sections with lower traffic volume (Projects 4077 and 4133). However, impacts per functional unit (in terms of user-miles traveled, VMT) are in the range of the other two projects. When VMT was used as functional unit, the sections with higher traffic volumes are given a credit due to serving for higher traffic while performing satisfactorily. In the case of project 4133, GWP impacts are highest (11.1 tonne-CO2-eq / mi VMT). This suggest that the project 4133 may not have an optimum design (in terms of structure) for the traffic condition it was built for.

Table 3. Use-stage Breakdown for GWP

LCA Stage	Component	GWP (tonne-CO_2-eq)			
		Project Code			
		4077	**4133**	**5228**	**723**
Use-stage	Roughness-Related Passenger Vehicle	25,144	35,950	93,047	114,648
	Roughness-Related Small Truck	624	1,483	2,577	2,018
	Roughness-Related Medium Truck	824	1,957	3,400	2,662
	Roughness-Related Large Truck	2,988	7,095	12,325	9,651
	Texture-Related Medium Truck	1,413	3,263	5,604	5,457
	Texture-Related Large Truck	2,738	6,324	10,860	10,576
	Albedo Mainline	3,148	6,943	1,111	-8,321
	Albedo Shoulders	2,087	7,423	1,056	-3,645
	Carbonation Mainline	-55	-111	-46	-116
	Carbonation Shoulders	0	0	0	0
Total (tonne-CO_2-eq.)		*38,915*	*70,331*	*129,939*	*132,931*
Total VMT (millions)		*4,199*	*6,354*	*12,451*	*20,921*
Per Functional Unit of Lane-Mile (LM) *tonne-CO_2-eq. / lane-mile*		**3,326**	**2,726**	**12,494**	**8,688**
Per Functional Unit of Annualized Lane-Mile (LMY) *tonne-CO_2-eq. / lane-mile-year*		**54**	**44**	**202**	**197**
Per Functional Unit of Vehicles Mile Travelled (VMT) *tonne-CO_2-eq. / million VMT*		**9.3**	**11.1**	**10.4**	**6.4**

According to the results albedo and carbonation only contribute to GWP and single score. In general, roughness effect governs use-stage impacts, followed by texture. The exception to this is GWP where the albedo effect is significant given the high surface exposure and change of albedo from new to weathered surface over time.

Different components of the use-stage contribute differently to the LCA indicators. This can result in the change of environmental rankings of comparable sections when different indicators are used. For example, since albedo and carbonation do not contribute directly to energy consumption, texture effect can be as high as 35% of energy indicators (TPE and PEF), however it is 20% (or less) of environmental indicators (SS and GWP) where albedo and carbonation contributions are involved.

Albedo can be a major contributor to GWP (~20%) when traffic is also relatively low. However, on overall environmental score (SS) of contributes less than 7%. Project 4133 in particular has the highest environmental (SS and GWP) impacts. This can be attributed to the relatively

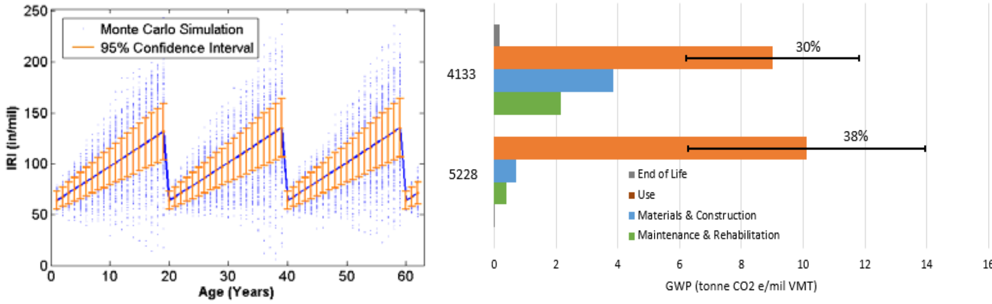


Figure 2. (a) IRI Progression with uncertainty band and (b) Resulting use stage output range

lower traffic, thus indicating a possible non-optimal design under current conditions.

Monte Carlo technique was used to run 1000 simulations of each project with probability distributions associated with IRI every year. The standard deviation of the measured IRI increases linearly from the initial value of 4.2 to 15.0 before rehabilitation. Figure 2-a shows the IRI progression for projects with 95% confidence interval calculated using Monte Carlo simulation. These uncertainties were propagated throughout the LCA analysis. Figure 2-b shows the resulting use stage GWP range. It can be noted that such small variations in the measurements can lead up to 30% change in the impact of the use stage. This is in line with the fact that pavement roughness is the main contributor to the overall project environmental impacts. Hence, measurement of the IRI and using appropriate use stage models are crucial for implementing pavement LCA. Therefore, the case studies highlighted the significance of a complete LCA with multiple use-stage components included, multi-point environmental performance evaluation and selecting an appropriate functional unit during the interpretation phase of a pavement LCA.

7 CONCLUSIONS

The development of a complete pavement LCA tool with an emphasis on the use-stage life-cycle stage is presented. The introduced framework aimed to address some of the current challenges in the area of pavement LCA by performing a comparative cradle-to-grave type of LCA using multi-point environmental performance evaluation and a proposed functional unit allowing for fair project-to-project comparison.

A functional unit was proposed that can be used in comparative LCAs to compare pavement systems with different performance and traffic characteristics. The proposed functional unit is based on the total vehicles travelling the section during the analysis period and designated as vehicle-length travelled (VLT), which can be implemented as vehicle-miles travelled (VMT) or vehicle-kilometer travelled (VKT). The unit provides a rational basis for comparative LCAs since it normalizes over years and traffic volume and does not necessarily penalize the longer living pavement systems carrying higher traffic volumes.

Four projects from the Illinois Tollway were selected to analyze the case studies. The projects were widening projects with jointed plain concrete pavement. In general, it was found that roughness and texture-related rolling resistance and resulting impacts constituted a significant portion of total use-stage impacts (between 50%-95% of total use-stage). Additional fuel consumption by passenger cars due to roughness was found to be responsible for the majority of the use-stage impacts. Albedo and carbonation only contribute to environmental indicators (GWP and SS) and not energy indicators (PEF and TPE). Albedo and the resulting radiative forcing can contribute significantly to GWP with relatively smaller effect on the overall environmental indicator (SS). GWP savings due to carbonation for concrete projects were less than 1%. Although the traffic level directly affected the total use-stage impacts, normalization of results by vehicle-miles traveled (VMT) allowed for a more reasonable interpretation of the results, consistent with the agency’s main goal to assess how much progress has been made over the years toward the sustainability goal by employing sustainable pavement strategies.

Also, uncertainty quantification of pavement roughness revealed that variations in IRI measurements can result in a significant change in the overall use stage results. Such significant impacts on the overall sustainability necessitate accurate measurements from the road network and the use of robust models in the LCA.

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9 REFERENCES

AzariJafari, H., A., Yahia & M. B. Amor. 2016. Life cycle assessment of pavements: reviewing research challenges and opportunities. *Journal of Cleaner Production*, *112*, 2187-2197.

Andersen, L. G., J. K., Larsen, E. S., Fraser, B., Schmidt & J. C., Dyre. 2014. Rolling resistance measurement and model development. *Journal of Transportation Engineering*, *141*(2), 04014075.

Bare, J. 2011. TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technologies and Environmental Policy*, *13*(5), 687-696.

Bare, J., T., Gloria & G. Norris. 2006. Development of the method and US normalization database for life cycle impact assessment and sustainability metrics. *Environmental science & technology*, *40*(16), 5108-5115.

Chatti, K. & I. Zaabar. 2012. *Estimating the effects of pavement condition on vehicle operating costs* (Vol. 720). Transportation Research Board.

Environmental Protection Agency (EPA). 2014. *MOVES (Motor Vehicle Emission Simulator).* Environmental Protection Agency, Washington, DC.

Gregory, J. R., Noshadravan, A., Olivetti, E. A., Kirchain, R. E. 2016. A Methodology for Robust Comparative Life Cycle Assessment Incorporating Uncertainty. *Environmental Science and Technology*, 50, 6397-6405.

Guinée, J.B., M., Gorrée, R., et al. 2002. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 2002, 692 pp. cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-

Harvey, J., Meijer, J., Ozer, H., Al-Qadi, I.L., Saboori, A., & Kendall, A. (2016). Pavement Life-Cycle Assessment Framework. Federal Highway Administration, Washington, DC.

Hammarström, U., J., Eriksson, R., Karlsson & M. R. Yahya. 2012. *Rolling resistance model, fuel consumption model and the traffic energy saving potential from changed road surface conditions*. VTI rapport, ISSN 0347-6030 ; 748A

Inyim, P., J., Pereyra, M., Bienvenu & A. Mostafavi. 2016. Environmental assessment of pavement infrastructure: A systematic review. *Journal of environmental management*, *176*, 128-138.

ISO. 28580. 2009. Passenger car, truck and bus tyres methods of measuring rolling resistance single point test and correlation of measurement results. The International Organization for Standardization.

ISO, I. 2006. 14040: Environmental management–life cycle assessment–principles and framework. *London: British Standards Institution*.

IEA. 2005. *Energy efficient tyres: Improving the on-road performance of motor vehicles*. In IEA Workshop. International Energy Agency, November 2005.

Kang, S., R., Yang, H., Ozer & I. L., Al-Qadi. 2014. "Life-Cycle Greenhouse Gases and Energy Consumption for the Material and Construction Phases of Pavement with Traffic Delay", *Transportation Research Record: Journal of the Transportation Research Board*, 2428(1), pp. 27-34.

Karlsson, R., U., Hammarström, H., Sörensen & O. Eriksson. 2011. Road surface influence on rolling resistance—Coastdown measurements for a car and HGV—VTI notat 24A. *Swedish Road Administration (VTI).*

Kaloush, K. E., J. D., Carlson, J. S., Golden & P. E. Phelan. 2008. *The thermal and radiative characteristics of concrete pavements in mitigating urban heat island effects* (No. PCA R&D SN2969).

Lautier, A., R. K., Rosenbaum, M., Margni, J., Bare, P. O., Roy & L. Deschênes. 2010. Development of normalization factors for Canada and the United States and comparison with European factors. *Science of the total environment*, *409*(1), 33-42.

Lagerblad, B. 2005. Carbon dioxide uptake during concrete life cycle–state of the art. *Swedish Cement and Concrete Research Institute CBI, Stockholm*.

Noshadravan, A., Wildnauer, M., Gregory, J., Kircahin, R. 2013. Comparative pavement life cycle assessment with parameter uncertainty. *Transportation Research Part D*. 25, 131-138.

Pommer, K. & C. Pade. 2006. Guidelines*: Update of Carbon dioxide in the Life Cycle Inventory of Concrete*." Norden, Nordic Innovation Centre, Norway.

Santero, N. J., E., Masanet & A. Horvath. 2011a. Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation and Recycling*, *55*(9), 801-809.

Santero, N. J. E., Masanet & A. Horvath. 2011b. Life-cycle assessment of pavements Part II: Filling the research gaps. *Resources, Conservation and Recycling*, *55*(9), 810-818.

Santero, N. J. & A. Horvath. 2009. Global warming potential of pavements. *Environmental Research Letters*, *4*(3), 034011.

Shakiba, M., H., Ozer, M., Ziyadi & I. L. Al-Qadi. 2016. Mechanics based model for predicting structure-induced rolling resistance (SRR) of the tire-pavement system. *Mechanics of Time-Dependent Materials*, 1-22.

Yang, R., Ozer, H., Al-Qadi., I.L., and W., Yoo. 2016. Development and Application of a Roadway/Roadside Life-Cycle Assessment Software for the Illinois Tollway. Submitted to *96th Annual Meeting, Transportation Research Board of National Academies*, Washington D.C.

Van Dam, T. J., Harvey, J.T. , Muench, S.T., Smith, K.D. , Snyder, M.B. , Al-Qadi, I.L. , Ozer, H. , Meijer, J., Ram, P.V., J.R. Roesler, J.R. & Kendall. A., 2015. *Towards sustainable pavement systems: a reference document*. Federal Highway Administration,: Washington, DC.

Wang, T., Harvey J., & A. Kendall. 2014. Reducing greenhouse gas emissions through strategic management of highway pavement roughness. *Environmental Research Letters*, 9.

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

Ziyadi, M., H. Ozer, S. Kang & I.L. Al-Qadi. 2016. Pavement Roughness Related Energy Consumption and Environmental Impact Calculation Model for Transportation Sector. *Environmental Research Letters* (submitted).