SCENARIO ANALYSIS OF COMPARATIVE PAVEMENT LIFE CYCLE ASSESSMENT USING A PROBABILISTIC APPROACH

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ABSTRACT

The field of pavement life cycle assessment (LCA) has been continuously evolving and improving over time, but several limitations still exist. We try to address some of these limitations by conducting comparative LCAs using a probabilistic approach, incorporating various sources of uncertainty in input data and varying important contextual parameters to identify the key drivers. This paper presents the results of a scenario analysis based on the comparative LCAs of thirty-four pavement scenarios. The effects of varying the scope of the analysis as well as the framing assumptions on the results of comparative pavement LCAs are discussed. In particular, the effect of excluding albedo effect from the use phase is explored. In addition, five parameters associated with the framing of analyses - climate zone, traffic level, maintenance schedule, design life and analysis period - are varied across all scenarios. The results show that the inclusion of the albedo effect has a significant impact on outcomes. In addition, climate zones and traffic levels affect the relative burden of the use phase on the overall environmental impact and are therefore also important. The significance of changes in design life and analysis period depends on the type of road being analyzed and whether the baseline periods are short or long.

INTRODUCTION

The field of pavement life cycle assessment (LCA) is relatively new, with the majority of work having been completed in the past decade *(1–3)*. While there have been important advances in the field, including the development of new life cycle inventory (LCI) data *(4)* and models to quantify impacts of pavement in the use phase *(5)*, there are still limitations in the ways that pavement LCAs are conducted and gaps in understanding of the key drivers in the analyses. For decision contexts aiming to select the pavement alternative with the lowest total impact, a key limitation is that the scope of many pavement LCAs does not include the use phase. Another is that nearly all pavement LCAs are deterministic. That is, they do not account for different sources of uncertainty such as inventory data, pavement designs, or maintenance schedules. The characterization of uncertainty is particularly important for pavement LCA given the state of current LCI data and pavement performance models and the long analysis periods inherent to such studies. Furthermore, a deterministic LCA cannot comment on the statistical significance of the difference between alternatives, nor the key drivers of variation in that difference. Finally, most LCAs only examine a few scenarios, and as such, it is not possible to understand the important elements that practitioners should focus on when conducting LCAs for other contexts.

We seek to address some of these limitations by analyzing a broad range of scenarios using a probabilistic approach. In particular, we would like to understand how the scope of the analysis (e.g., the inclusion of different elements of the use phase) affects the outcomes of comparative LCAs (i.e., when the focus of the analysis is on the comparison of multiple alternatives). In addition, we would like to understand how the framing of analyses (specifically, climate zone, traffic level, maintenance schedule, design life, and analysis period) affects the outcomes of comparative LCAs. In order to gain this understanding we have conducted comparative analyses of two alternative pavement designs in thirty-four different scenarios. Although the scope of these scenario analyses is certainly not comprehensive, it is broad enough to begin to provide insight on the important elements that practitioners should consider when conducting pavement LCAs. The probabilistic approach helps us understand the key drivers of the analyses and how they vary by scenario. It is important to note that the purpose of this scenario analysis is not to draw conclusions about specific pavement designs or materials. Rather, we are using the pavement designs as a mechanism for exploring the sensitivity of pavement LCA to scoping and framing decisions and this is best accomplished by using a broad range of meaningful scenarios. However, analyses based on other pavement designs, framing assumptions, or contexts may come to different comparative conclusions.

METHODOLOGY

Pavement Life Cycle Assessment Model

The pavement life cycle assessment model used in these analyses is described in detail by Noshadravan et al. *(6)* *,* but key elements are summarized here; additional details on the model are provided in Chapter 2 of the supporting information *(7)*. The scope of the model is presented in Figure 1. Of particular note is the use phase (as defined in the pavement LCA literature), which includes quantification of impacts from albedo, carbonation, lighting, roughness-derived pavement-vehicle interaction (PVI), and deflection-based PVI.

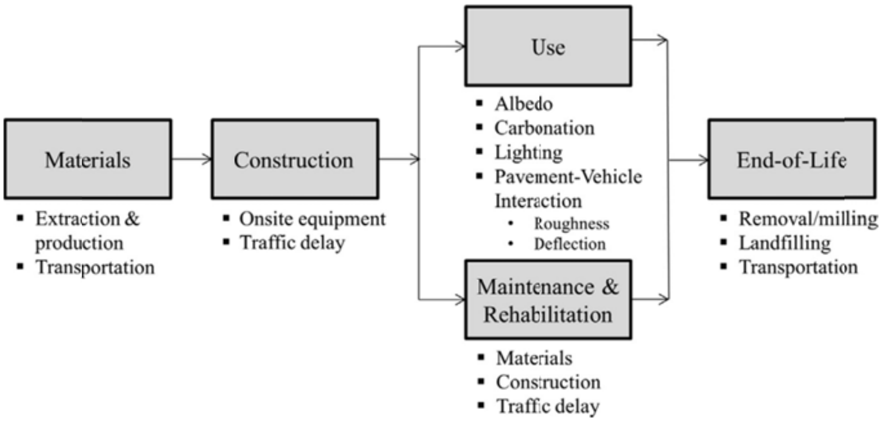


Figure 1: Scope and boundary of pavement LCA.

Albedo accounts for the effect of solar reflectance of a pavement on the global warming potential. Two major effects associated with albedo are radiative forcing and urban heat island. Radiative forcing accounts for the direct reflectance of the incoming solar radiation, while urban heat island indirectly contributes to global warming by increasing the ambient temperature and the energy demand for cooling devices. According to a study in Los Angeles, pavements comprise one-eighth of the urban surface area (roofs account for another one-eighth of the area) *(8)*. Because they represent a relatively large fraction of the total surface area, pavements are the primary targets for albedo increases, making this a noteworthy element of the pavement life cycle. The carbon dioxide-equivalent offset attributed to the reflectivity of the pavements can be estimated based on the work of Akbari et al. *(9)*, as has been done in many pavement LCA studies *(10).* Akbari's model uses an offset rate of 2.55 kg CO_2-e/m^2 due to increased radiative forcing over the entire life of a pavement, and an offset of 4.85 g CO_2-e/m^2 per year due to decreased electricity consumption for every 0.01 increase of albedo *(11)*. It is important to note that while the physical mechanism that underlies albedo is well documented, there is still uncertainty about their extent in real-world pavement installations. To reflect this, significant uncertainty is assigned to the magnitude of each of these effects.

The albedo of a pavement is characterized by a dimensionless number, which varies from 0 (fully absorbent) to 1 (fully reflective). The estimation of offset also requires a baseline value of reflectivity with respect to which an equivalent carbon dioxide quantity is calculated. In this work we set the baseline value to 0.33, which roughly represents the average reflectivity of the earth. Quantitative information on the evolution of pavement albedo over time is not available and thus, ranges of 0.25-0.4 are used for concrete pavements and 0.05-0.2 are used for asphalt pavements *(11)*. In the probabilistic analysis, pavement albedo is treated as a random variable. In each run of the simulation, a constant value is selected randomly from the range to represent the average pavement albedo over the entire analysis period. The CO_2 offsets due to radiative forcing and urban heat island are calculated using the following equations:

$$m_{CO_2,RF} = \frac{\Delta\alpha}{0.01} \times A \times Ef_{RF} \tag{1}$$

$$m_{CO_2,UHI} = \frac{\Delta\alpha}{0.01} \times A \times Ef_{UHI} \times t \tag{2}$$

where:

$\Delta\alpha$ is the change in albedo calculated with reference to a baseline albedo 0.33, A is the surface area of the pavement, $Ef_{RF} = 2.55\,\mathrm{kg\,CO_2e/m^2}$, is a one-time offset of CO_2 emissions per 0.01 change in albedo over the life of pavement, $Ef_{UHI} = 4.85\,\mathrm{g\,CO_2e/m^2}$, is an annual CO_2 emission per 0.01 change in albedo, and t is the analysis period.

Pavement-vehicle interaction (PVI) accounts for the extra fuel consumption in the vehicles on the road caused by the change in the structural and surface properties of pavements. It is important to emphasize that this is not the entire burden of fuel use, but rather the effect of pavement properties on the fuel economy of vehicles. Two major sources of PVI include fuel losses due to changes in roughness and fuel losses due to deflection of the pavement. Our LCA model accounts for both roughness and deflection components. It is important to note that both the impact of maintenance on PVI and the improvement of vehicle fuel economy are taken into account in this model.

The deflection losses are calculated based on the model developed by Akbarian et al. *(5)*. The model uses a mechanistic approach to predict the deflection of the road over its lifetime as a function of the structural properties of the pavement. The predicted deflection can then be translated to the associated increase in the fuel loss relative to a fully rigid pavement. This is a novel model which has been calibrated to national highway performance values. Further extensions and refinements to the model continue and thus, an associated level of uncertainty was ascribed to the model predictions. To reflect this, a significant level of uncertainty was ascribed to the predictions of this model. Roughness is characterized by the international roughness index (IRI). The prediction of IRI over time is extracted from output of the pavement design software, Pavement-ME, which implements the calculations specified by the Mechanistic-Empirical Pavement Design Guide (MEPDG) *(12,13).* The progressive change in the roughness relative to its value at initial construction is calculated and translated to the extra fuel consumption using the empirical model presented by Zaabar and Chatti *(14).* Equation (3) and (4) show the calculations of the emissions from roughness and deflection induced PVI:

$$GWP_{IRI} = \sum_{t=1}^{T} \Delta IRI_t \times (\Delta AADTT_t \times K_{fc_{truck}} \times EF_{diesel} + \Delta AADT_t \times K_{fc_{car}} \times EF_{gas}) \times t \qquad (3)$$

Where

ΔIRI_t is the change in IRI within time interval *t*, $\Delta AADTT_t$ and $\Delta AADT_t$ are truck and car traffic during t, $K_{fc_{truck}}$ and $K_{fc_{car}}$ are the coefficients that translates ΔIRI into fuel consumption derived from Zaaba and Chatti's calibration of HDM-4 model, and EF_{diesel}, EF_{gas} are the GWP emission factors for diesel and gas.

$$GWP_{DEF} = \sum_{t=1}^{T} f_{truck}(E,k,h)_t \times \Delta AADTT_t \times EF_{diesel} + f_{car}(E,k,h)_t \times \Delta AADT_t \times EF_{gas}) \times t \qquad (4)$$

Where

$f_{truck}(E,k,h)_t$ and $f_{car}(E,k,h)_t$ are fuel consumptions for trucks and cars in time *t* as functions of elastic modulus *E*, subgrade modulus *k* and pavement thickness *h*, calculated from MIT deflection model.

Our pavement LCA model can be used to calculate any number of life cycle impact assessment metrics, but in this paper we present results in terms of global warming potential (GWP) based on factors calculated by the Intergovernmental Panel on Climate Change (IPCC). The specific LCI data and calculations for all activities in the model are described in Chapter 2.3 of the supporting document online *(7)*.

Probabilistic Approach

A complete description of our probabilistic pavement LCA methodology can be found in *(6)*. There are three primary steps in this approach which are summarized here: uncertainty characterization and propagation, probabilistic assessment, and scenario analysis.

Uncertainty Characterization and Propagation

Pavement LCA depends on a variety of data that define a specific analysis. Given the scope and nature of life cycle assessment, significant uncertainty is associated with much of that data. For the analyses presented here, probability distributions have been associated with most modeling parameters. These distributions were characterized either from available empirical data or expert estimates based on the *Ecoinvent* guidelines *(15)*. This includes the parameters used to describe pavement design and maintenance, other LCI data, and the impacts of upstream processes (such as electricity generation or truck transportation). More information on the uncertainty characterizations for the parameters used in this study can be found in Chapter 2 of the supporting document *(7)*.

Monte Carlo simulation is performed to propagate the parameter uncertainty into the estimated life cycle GWP using a computational LCA model we have developed. In each run of the simulation, a set of parameter samples are drawn from their corresponding distributions, and the life-cycle GWPs are calculated for both concrete and asphalt pavement designs simultaneously. Where appropriate, a common sample is used for both designs to account for the natural correlation that would exist across two alternative designs constructed in the same location. The calculations are repeated N times, resulting in N realizations of GWP. From these realizations, the statistical characteristics of GWP can be estimated. The results presented here are based on 10,000 simulations for each scenario.

Comparative Assessment

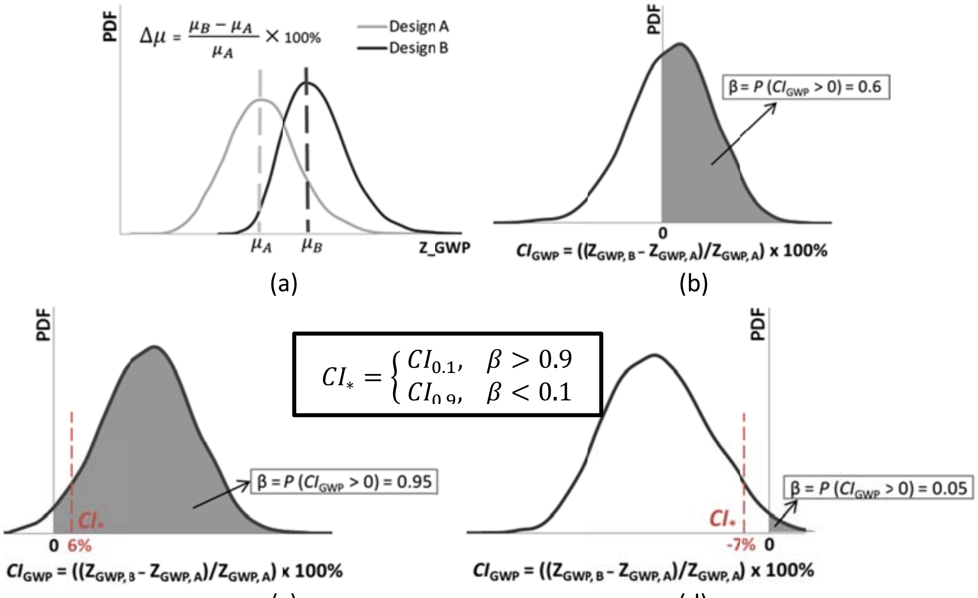
To statistically compare environmental impacts, in our case the GWP of two alternative pavement designs, we make use of a comparison indicator CI_{GWP} defined as the normalized difference between two alternatives, $CI_{GWP} = ((Z_{GWP,\,B} - Z_{GWP,\,A})/Z_{GWP,\,A}) \times 100\%$, where $Z_{GWP,i}$ is the GWP of alternative *i*. $CI_{GWP} > 0$ means design A has lower GWP than design B for a specific simulation. As a probabilistic measure of comparison, we introduce a metric which characterizes the likelihood that one design has lower impact than another across all simulations: $\beta = P\,(CI_{\mathrm{GWP}}>0)$. This metric β measures the relative difference in the performance of two designs in a statistical manner. By comparing β to a prescribed threshold, a decision-maker can identify that design A is better than design B, B better than A, or that no conclusion is justified. This threshold is a decision parameter, selected by the decision-maker, which controls the level of risk associated with the decision. To discuss the results presented here, we use a threshold of 0.9. This number was chosen because it seemed to provide a reasonable balance between the need for providing actionable guidance (i.e., a lower threshold which increases the ability to identify a preferred alternative) with the risk of incorrectly identifying the preferred alternative (i.e., a higher threshold). (Note that alternatively one can look at $1 - \beta$ as the likelihood that design B has lower impact than design A). If β is greater than the threshold 0.9 (or less than 0.1), we consider the difference between the two alternatives as statistically significant. In addition to the metric β, we also calculate the value of the comparison indicator when β is 0.9 (or 0.1), denoted as CI_*. This value represents the maximum statistically significant difference between the two alternatives. The CI_* metric is only meaningful when a statistically significant difference exists (i.e., when β is greater than 0.9 (or less than 0.1). These concepts are depicted in Figure 2.

Finally, we calculate the percent difference in the means of the GWP distributions for the two alternatives, $\Delta\mu$, which is defined in Figure 2a. This is used for comparison with the CI_* value because it can be considered as the conventional metric for comparing life cycle impacts in deterministic LCAs. The differences in means, however, do not provide any information on the statistical significance of the difference between alternatives.

Scenario Analysis

While the probabilistic approach propagates uncertainty for most parameters, the impact of some parameters or framing decisions on the outcomes of LCA are more suited to analysis through individual scenarios. In this analysis five parameters fit this profile and are varied to meet the objectives of the analysis outlined in the Introduction. A total of thirty-four different scenarios were created based on combinations of the five parameters and are summarized in Table 1. The five parameters and their values are as follows.

- **Climate zone.** Four states representing four major climate zones from the Federal Highway Administration's Long-Term Pavement Performance (LTPP) program are used in this analysis: Arizona, Colorado, Florida, and Missouri. Beyond the range of climate zones, these specific states were selected because local calibrations of MEPDG models were available.
- **Traffic level.** Typical average annual daily truck traffic (AADTT) for three different situations are used: rural local highway, state highway, and urban Interstate highway.



(a) (b)

(c) (d)

Figure 2: Illustrations of metrics used for comparative LCA.

(a) Difference between design A and B impact relative to design A using the mean values; (b) The likelihood that design A has lower impact than design B, i.e. β = *P* ($CI_{\text{GWP}} > 0$) = 0.6, indicating a statistical tie between the two designs; (c) Design A has statistically significant lower impact than design B, i.e. β = *P* ($CI_{\text{GWP}} > 0$) = 0.95. CI_* = 6% means the maximum statistically significant difference is 6%; (d) Design B has statistically significant lower impact than design A, i.e. β = *P* ($CI_{\text{GWP}} > 0$) = 0.05. CI_* = -7% means the maximum statistically significant difference is 7%.

Table 1: Overview of Scenarios (DL = design life, AP = analysis period)

Two analyses were conducted for each case outlined in the table: one with a DOT-derived maintenance schedule and one with an MEPDG-derived maintenance schedule. This leads to a total of 34 scenarios.

Traffic Level 2-Direction AADTT	LTPP Climate Zone			
	Wet Freeze (Missouri)	Dry No Freeze (Arizona)	Dry Freeze (Colorado)	Wet No Freeze (Florida)
Local Street/Highway (Rural) AADTT = 300	**1.** DL=20, AP=50 **2.** DL=30, AP=50	(N/A)	(N/A)	(N/A)
State Highway (Rural) AADTT = 1,000	**3.** DL=20, AP=50 **4.** DL=30, AP=50 **5.** DL=40, AP=50	**6.** DL=30, AP=50	**7.** DL=30, AP=50	**8.** DL=30, AP=50
Interstate (Urban) AADTT = 8,000	**9a.** DL=20, AP=30 **9b.** DL=20, AP=50 **10a.** DL=30, AP=50 **10b.** DL=30, AP=75 **11a.** DL=50, AP=75 **11b.** DL=50, AP=100	**12.** DL=30, AP=50	**13.** DL=30, AP=50	**14.** DL=30, AP=50

- **Maintenance schedule.** Two types of maintenance schedules are used: an agency or department of transportation (DOT)-derived schedule and an MEPDG-derived schedule. The DOT schedule is based on standard maintenance practices prescribed by a DOT for life cycle cost analysis in the specific state, whereas the MEPDG schedule is derived from the MEPDG prediction of pavement distress over time. Different distress types were taken into account in when evaluating when the pavement would require maintenance including roughness, rutting, cracking, and faulting.

- **Design life (DL).** Design life is defined as the time to the first rehabilitation (full depth repair for concrete and milling/overlay for asphalt). Three alternatives are used that encompass a range of standard practice in pavement LCAs: a baseline of 30 years and two alternatives depending on the traffic level (20 years or 50 years).
- **Analysis period (AP):** Four variations are used that also encompass a range of standard practice in pavement LCAs: a baseline of 50 years and three alternatives depending on the traffic level and design life (30 years, 75 years, or 100 years).

An independent pavement design firm (Applied Research Associates) created functionally equivalent flexible (asphalt in the top layer) and rigid (concrete in the top layer) pavement designs and maintenance schedules for each scenario using the Pavement-ME software and associated MEPDG models. Details on the designs and the maintenance schedules are summarized in supporting document (Chapter 4 to 20)*(7)*. These two types of pavement designs were selected because they are often compared in pavement type selection and alternate design/alternate bid processes by DOTs when constructing new pavements. The pavement design firm made every effort to make sure the designs and maintenance schedules are functionally equivalent, but there are certainly other solutions available for these contexts. As such, the outcomes of these analyses are intended to be meaningful but not definitive. The functional unit in all analyses is one center-lane mile of pavement.

Limitations

As with any analysis, ours has limitations. First, the materials and construction practices (including end-of-life) and associated LCI data used in these analyses are limited to conventional versions of each. The use of lower environmental impact materials (e.g., portland limestone cement or warm mix asphalt) or construction methods (e.g., cold in-place asphalt recycling) would likely impact the outcomes of this analysis, although LCI data on many of these innovative practices is scarce. Second, we have not forecast any changes in LCIs used in future maintenance activities due to challenges associated with these predictions. Third, although we have incorporated uncertainty into most aspects of the life cycle inventory, we have not accounted for uncertainty in the life cycle impact assessment method (i.e., IPCC GWP factors), nor have we implemented time-adjusted GWP factors as proposed by Kendall in *(16)*, which will be explored in future work. Fourth, we do not address uncertainty in co-product allocation, as analyzed by Huang et al *(17)*.

The MEPDG models used in pavement design are continuously improving and as a consequence, more recent versions of these models may make different predictions about pavement distresses over time than the ones used in this analysis, which would impact roughness and maintenance timing predictions and therefore impact comparative LCA outcomes. Thus, future analyses should make use of the most recent MEPDG models. Finally, each scenario in this analysis uses one maintenance schedule for the entire analysis period. Even though we account for uncertainty in the timing of the maintenance activities, in reality there is uncertainty in the types of activities that would be conducted as well. A promising technique has recently been proposed to explore this type of uncertainty using decision tree analysis *(18).* The feasibility of incorporating this technique into our probabilistic approach will also be explored in future work.

RESULTS

Our first objective in this analysis is to understand how scope affects the outcomes of comparative pavement LCAs, with particular emphasis on the albedo effect. Although it is possible to estimate the environmental impact of the albedo effect in a pavement LCA, the current modeling practice assumes that both the albedo factors used for the pavements and the CO_2 offset value are independent of the specific context in the analysis. That is, unlike predictions of pavement distress and PVI, the characterization of the albedo effect does not depend on the location of the analysis because reliable long-term location-specific data on pavement albedo is not available. Thus, although we can calculate an estimate of the impact of the albedo effect on pavement LCA and choose to do so in order to gain an understanding of the magnitude of the effect, it is also understandable to exclude albedo from the use phase in pavement LCAs. As such, we would like to understand the impact of excluding albedo from the scope of the analysis. Table 2 presents the results of the full-scope (i.e., all life cycle phases and related sub-components included) and reduced-scope (i.e., all life cycle phases, except albedo effect excluded from the use-phase) comparative LCA using the baseline pavement design scenarios of 30-year design life and 50-year analysis period, and MEPDG-derived maintenance schedule.

Table 2: Full-Scope and Reduced-Scope Comparative LCA GWP Results from 1 mile Rigid and Flexible Pavement Designs with DL= 30, AP= 50, and MEPDG-Derived Maintenance Schedule

Metrics in table: Δμ = %difference at means; β = P ($CI_{\text{GWP}} > 0$); CI_* = CI @ β = 0.9 or 0.1 depending on β value; black background means flexible design has statistically significant lower impact; grey background means rigid design has statistically significant lower impact

Traffic Level 2-Direction AADTT		LTPP Climate Zone			
		Wet Freeze (Missouri)	**Dry No Freeze (Arizona)**	**Dry Freeze (Colorado)**	**Wet No Freeze (Florida)**
		Δμ, β, CI_*	Δμ, β, CI_*	Δμ, β, CI_*	Δμ, β, CI_*
Local Street/Highway (Rural) AADTT = 300	Full-scope	26%, 0.94, 5%	(N/A)	(N/A)	(N/A)
	Albedo excluded	-14%, 0.14, (N/A)			
State Highway (Rural) AADTT = 1,000	Full-scope	37%, 0.98, 14%	39%, 0.99, 16%	68%, 1.00, 52%	49%, 1.00, 24%
	Albedo excluded	-2%, 0.46, (N/A)	2%, 0.57, (N/A)	33%, 0.98, 11%	5%, 0.65, (N/A)
Interstate (Urban) AADTT = 8,000	Full-scope	1%, 0.57, (N/A)	35%, 0.99, 15%	26%, 0.93, 4%	24%, 0.94, 4%
	Albedo excluded	-14%, 0.18, (N/A)	14%, 0.86, (N/A)	6%, 0.68, (N/A)	4%, 0.63, (N/A)

The metrics in Table 2 were defined in Figure 2. For all results presented in this section, design A is the rigid design and design B is the flexible design. Thus, positive values for Δμ indicate that the mean of the rigid design has a lower impact than the mean of the flexible design, and the percentage is this difference relative to the rigid design. A negative value for Δμ indicates that the mean of the flexible design is lower than the mean of the rigid design. The meaning of positive and negative values is the same for *CI.* Furthermore, a β > 0.9 means the rigid design has a statistically significant lower impact. CI_* represents the *CI* when β = 0.9, which is the maximum statistically significant difference between the two alternatives (see Figure 2 for clarification), even though the probabilistic analysis will calculate a range of differences between alternatives (including the means). A similar result can be identified when

$\beta < 0.1$ (when the flexible design has statistically significant lower impact).In that case, CI_* is defined as the CI when $\beta = 0.1$. No CI_* value is provided when $0.1 < \beta < 0.9$ because the difference is not statistically significant; i.e., it is a statistical tie.

The results in Table 2 indicate that for the full-scope analysis, statistically significant differences exist in all scenarios except the Missouri interstate highway. It is instructive that statistically significant maximum percent differences CI_* are all smaller than the differences in the means. For example, the difference in means for the Florida state highway is 37%, but the maximum statistically significant difference is 18%.

The most obvious difference between the full-scope and reduced-scope analysis is that eight of the nine scenario results are statistically significant for full-scope analysis, whereas only one scenario is significantly different when excluding albedo from the scope. In addition, the CI_* values for reduced-scope analysis are smaller than full-scope analysis, meaning that the maximum statistically significant differences between the alternatives are narrower when albedo is excluded. This implies that the inclusion of the albedo effect has a significant impact in favor of the rigid designs, which is caused by its higher albedo values. Given that calculating location-specific albedo impacts is currently infeasible, we will use the results of reduced-scope analysis (excluding albedo) as our baseline going forward in this paper.

Table 3 summarizes the contribution of each life-cycle phase to the total GWP at mean values based on the comparative LCA results with albedo effect excluded from the scope using the same scenarios (DL = 30, AP = 50 and MEPDG maintenance schedule). In each cell, the flexible pavement design is on the left while rigid design on the right. The y-axis on the left indicates the GWP in Mg CO_2 per mile of pavement.

Comparing the breakdowns of the total GWP for flexible and rigid designs, it is evident that the impact of use phase becomes more significant as traffic level increases from local/state highways to urban interstate highways. Although the rigid pavement designs require minimal maintenance activities as compared to the flexible pavement designs, in most cases (except Missouri and Colorado interstates) the contributions of the higher initial construction impacts to the total impact tend to offset the future reduced maintenance benefits.

We also conducted sensitivity analyses on these results and the specific drivers and their order depend on the scenario, but in general the top contributors to the variance in the *difference* of the results (as opposed to the individual results of each alternative) are the roughness prediction (described in *(6)*), the upstream life cycle environmental impacts for both cement and asphalt, the thickness of the concrete layer in the pavement, and the energy required in the construction of asphalt pavements. It is important to note that the contribution to the variance is a combination of both the degree to which the parameter contributes to the total and the amount of uncertainty in the parameter.

Another topic of interest in our analysis is the impact of the maintenance schedule used in the analysis. Table 4 shows the comparative LCA results with albedo excluded from the scope using the same scenarios (DL = 30, AP = 50) with the DOT maintenance schedule as compared to the MEPDG schedule. Comparing the results in Table 4, it is evident that the β values are higher for the DOT maintenance schedule scenarios, indicating that these scenarios favor the rigid pavement designs. The likely explanation for this is that the DOT maintenance schedules predict more maintenance for flexible designs than the MEPDG schedules.

Table 3: Contribution to Total GWP by Phases with Albedo Excluded from Scope from 1 mile Rigid and Flexible Pavement Designs with DL= 30, AP= 50, and MEPDG-Derived Maintenance Schedule.

M&R = Maintenance and Rehabilitation; EOL = End-of-Life. The relative heights of the bars are proportional to the total impacts at the means

<table>
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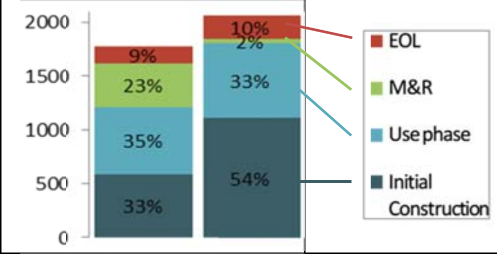
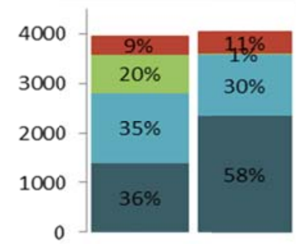
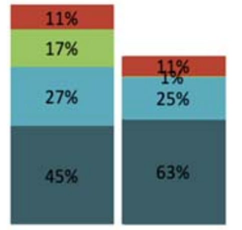
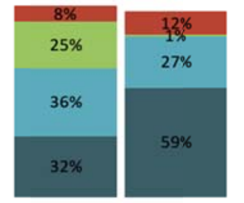
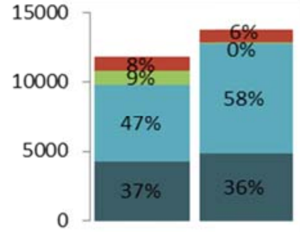
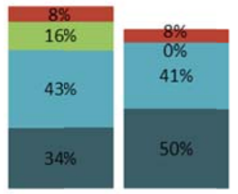
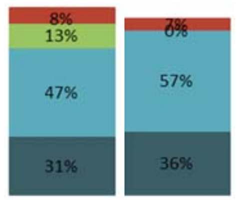
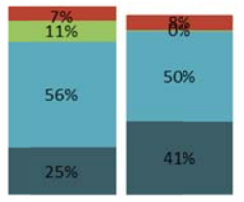
<tr><th colspan="3">Wet Freeze (Missouri)</th><th colspan="2">Dry No Freeze (Arizona)</th><th colspan="2">Dry Freeze (Colorado)</th><th colspan="2">Wet No Freeze (Florida)</th></tr>
<tr><th>Mg CO_2</th><th>Flexible</th><th>Rigid</th><th>Flexible</th><th>Rigid</th><th>Flexible</th><th>Rigid</th><th>Flexible</th><th>Rigid</th></tr>
<tr><td>Local Street/ Highway (Rural) AADTT = 300</td><td colspan="5"> </td><td colspan="2">(N/A)</td><td colspan="2">(N/A)</td></tr>
<tr><td>State Highway (Rural) AADTT = 1,000</td><td colspan="3"> </td><td colspan="2"> </td><td colspan="2"> </td><td colspan="2"> </td></tr>
<tr><td>Interstate (Urban) AADTT = 8,000</td><td colspan="3"> </td><td colspan="2"> </td><td colspan="2"> </td><td colspan="2"> </td></tr>
</table>

The final topic of interest is the impact of design life and analysis period on the outcomes of the comparative LCAs. Table 5 presents the comparative LCA results for Missouri scenarios only with albedo excluded from the scope and multiple combinations of design life and analysis period. Comparing 20 and 30 year DL for a 50 year AP, and 30 and 50 year DL for a 75 year AP, we see that increasing the design life results in small decreases in β values. This implies that longer design lives have a slight tendency to favor flexible pavements in this location. Changing the analysis period in the interstate scenario has less predictable consequences. At shorter design lives and analysis periods, the impact of analysis period is significant, whereas at longer design lives and analysis periods, the impact of analysis period is less significant. The impact of design lives and analysis periods on comparative LCA outcomes should be explored for other contexts in order to understand the sensitivity of these outcomes to location.

Table 4: Comparative LCA GWP Results from 1 mile Rigid and Flexible Pavement Designs with DL= 30, AP= 50, Comparing MEPDG-Derived and DOT-Derived Maintenance Schedule

Metrics in table: Δμ = %difference at means; β = *P* ($CI_{\mathrm{GWP}} > 0$); CI_* = *CI* @ β = 0.9 or 0.1 depending on β value; black background means flexible design has statistically significant lower impact; grey background means rigid design has statistically significant lower impact

Traffic Level 2-Direction AADTT		LTPP Climate Zone			
		Wet Freeze (Missouri)	Dry No Freeze (Arizona)	Dry Freeze (Colorado)	Wet No Freeze (Florida)
		Δμ, β, CI_*	Δμ, β, CI_*	Δμ, β, CI_*	Δμ, β, CI_*
Local Street/Highway (Rural) AADTT = 300	MEPDG	-14%, 0.14, (N/A)	(N/A)	(N/A)	(N/A)
	DOT	-7%, 0.32, (N/A)			
State Highway (Rural) AADTT = 1,000	MEPDG	-2%, 0.46, (N/A)	2%, 0.57, (N/A)	33%, 0.98, 11%	5%, 0.65, (N/A)
	DOT	5%, 0.65, (N/A)	7%, 0.70, (N/A)	39%, 0.99, 17%	15%, 0.86, 0%
Interstate (Urban) AADTT = 8,000	MEPDG	-14%, 0.18, (N/A)	14%, 0.86, (N/A)	6%, 0.68, (N/A)	4%, 0.63, (N/A)
	DOT	-14%, 0.17, (N/A)	37%, 0.99, 14%	35%, 0.98, 11%	12%, 0.82, (N/A)

Table 5: Comparative LCA GWP Results with Albedo Excluded from Scope from 1 mile Rigid and Flexible Pavement Designs with Various Combinations of Design Life and Analysis Period and MEPDG-Derived Maintenance Schedule

Metrics in table: Δμ = %difference at means; β = *P* ($CI_{\mathrm{GWP}} > 0$); CI_* = *CI* @ β = 0.9 or 0.1 depending on β value; black background means flexible design has statistically significant lower impact

Traffic Level 2-Direction AADTT	Wet Freeze (Missouri)				
	DL	AP	Δμ	β	CI_*
Local Street/Highway (Rural) AADTT = 300	20	50	-11%	0.12	(N/A)
	30	50	-14%	0.14	(N/A)
State Highway (Rural) AADTT = 1,000	20	50	-3%	0.38	(N/A)
	30	50	-2%	0.46	(N/A)
	40	50	-4%	0.37	(N/A)
Interstate (Urban) AADTT = 8,000	20	30	-5%	0.37	(N/A)
	20	50	-11%	0.23	(N/A)
	30	50	-14%	0.18	(N/A)
	30	75	-12%	0.22	(N/A)
	50	75	-15%	0.16	(N/A)
	50	100	-19%	0.14	(N/A)

CONCLUSIONS

In closing, we will revisit the original objectives of the paper and comment on our understanding of comparative pavement LCAs based on the knowledge gained in this scenario analysis with a probabilistic approach. We sought to understand the impact of scope and five framing assumptions on the outcomes of comparative pavement LCAs.

Scope of analysis: We can see from comparing results in Table 2 that the exclusion of use phase elements, specifically albedo, can have a significant impact on the outcomes of the analysis. In particular, the inclusion of albedo favors more reflective pavements. The development of location-specific albedo models would improve the confidence and accuracy of pavement LCAs.

Climate zone: Comparing results across climate zones in Table 2 we see that the results are fairly consistent for state highways, but are more variable for interstates. Indeed, none of the interstate scenarios have statistically significant results when albedo is excluded. In the case of wet freeze climate in Missouri, flexible pavement design is more favorable. This is due to the fact that flexible design deteriorates faster in cold weather and thus requires maintenance before IRI meets the critical value of failure, which results in less roughness-induced GWP. In addition, the roughness for the rigid design evolves at a faster rate when compared to other criteria for maintenance, thus introducing larger PVI impact. By contrast, the dry climates generally favor the rigid pavement designs due to lower roughness evolution rates.

Traffic level: From Table 3 we see that as traffic levels increase the use phase impacts become more important, regardless of location. This is due to the fact that PVI effects are directly proportional to traffic levels. Given the importance of the use phase, pavement LCAs should incorporate this element and traffic levels should be modeled carefully.

Maintenance schedule: The results in Table 4 show that the selection of maintenance schedule can significantly influence the analysis. In this analysis the MEPDG maintenance schedules favored the flexible pavement designs as they predict less maintenance for both designs, but this impacts the flexible designs more than the rigid designs. This implies that pavement LCAs should consider multiple maintenance alternatives, including uncertainty in the timing and nature of the maintenance.

Design life: For the location of Missouri, design life changes for the state highway had minimal impact on the comparative outcomes, whereas impacts were more pronounced for the local street and interstate. Because there are numerous strategies that may be used to meet design life targets, additional strategies should be explored before drawing broader conclusions.

Analysis period: Changes in analysis period were only examined for the Missouri interstate. In this context, at shorter design lives and analysis periods, the impact of analysis period is significant, whereas at longer design lives and analysis periods, the impact of analysis period is less significant. Thus, the selection of longer design lives and analysis periods may minimize the impact of uncertainty due to these factors. However, it is difficult to draw general conclusions from this single context. Thus, this issue should be explored further using other contexts.

Many of the insights from this analysis can be used to guide other LCAs, but specific outcomes will always depend on the combination of pavement designs, maintenance strategies, context, and LCI data.

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