UNCERTINATY MANAGEMENT IN COMPARATIVE LIFE-CYCLE ASSESSMENT OF PAVEMENTS

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ABSTRACT

There is significant uncertainty and variation in the environmental life cycle assessment of pavements. Uncertainty and scenario variation should be sufficiently accounted in the comparative life cycle assessment in order to increase the confidence on decisions regarding the environmental implications of alternative pavement systems. In this paper we first present a probabilistic approach for conducting comparative environmental life cycle analysis of pavements under uncertainty and variation. Making use of this model, we then examine the effect of variation in design life and analysis period on the results of comparative life cycle global warming potential of pavements. Two types of pavement alternatives under four different scenarios are compared. These scenarios are defined by prescribing different sets of values for the design life and analysis period. This information is used to quantify the degree by which the conclusion regarding the environmental superiority of the pavement choices under study is influenced by the variation in the design life and the analysis period. The results indicate that for the presented case study the variation in the design life and the analysis period does not lead to a different decision regarding the environmental advantage of these two pavement types.

KEY WORDS

PAVEMENTS / LIFE CYCLE ASSESSMENT / ENVIRONMENTAL IMPACTS / UNCERTAINTY.

1. INTRODUCTION

There is a growing interest in environmentally conscious design of road transportation systems. As such decisions around alternative products and designs involve a balance of three main factors: performance, cost, and environmental impact. Methodologies and tools are required to quantify these factors. The Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO, 2008; NCHRP, 2004) has been increasingly used among pavement engineers as a mechanistic-based approach to predict the pavement performance of the pavements over their lifetimes. Life cycle assessment (LCA) is the main technique to evaluate the environmental impacts of products and systems. It has also been employed to estimate the environmental implications of pavements (Häkkinen & Mäkelä, 1996; Horvath & Hendrickson, 1998; Meil, 2006; Stripple, 2001). An LCA model for pavements depends on a variety of input parameters. These parameters define different characteristics of the model such as pavement design specifications, material and energy flows, environmental impact quantities, etc. There is often uncertainty associated with the data and input parameters. Moreover, there is variation associated with different scenarios under which the pavements are designed or intended to be used. These scenarios are defined by prescribing the temporal boundary (design life, analysis period), operational context (traffic, climate, etc.), and performance criteria. Uncertainty and scenario variation should be sufficiently accounted in the comparative life cycle assessment in order to draw a more credible conclusion on the superiority of different alternatives. One of the sources of variation in the process of pavement LCA is the temporal boundary of the system. Specifically, the design life and analysis period define important aspects of the temporal scope of the system to be analyzed and, generally speaking, there is no true value for these parameters. The consequence of different practices in setting these temporal parameters on the environmental impacts of pavements, however, needs to be studied in order to shed light on incorporating environmental perspective into the decision making process. The way these parameters influence the results of comparative life cycle assessment can be complex due to inherent parameter uncertainty in the process of life cycle impact assessment, as well as the uncertainly in the prediction of pavement performance.

In this paper we first present a probabilistic approach for conducting comparative environmental life cycle analysis of pavements under uncertainty and variation. Making use of this model, we then examine the effect of variation in design life and analysis period on the results of comparative life cycle global warming potential (GWP) of pavements. For this purpose, the life cycle assessment model that takes into account the major sources of parameter uncertainty is used to compare two pavement alternatives under four different scenarios. These scenarios are defined by prescribing different sets of values for the design life and analysis period of a given pavement design. This information is used to quantify the degree by which the conclusion regarding the environmental superiority of the pavement choices under study is influenced by the variation in the design life and the analysis period.

2. METHODOLOGY

2.1 Life cycle assessment model

Life cycle assessment can be used to quantify the environmental impacts of pavements. A full pavement LCA model often compromises five main phases (Santero & Horvath, 2009; Yu & Lu, 2012): material extraction, construction of the pavement, use phase, maintenance and rehabilitation, and finally end-of-life. Figure 1 depicts the five phases and the major subcomponents associated with these phases. A detail description of the life cycle model is presented in (Noshadravan et al, 2013). Most of the life cycle phases have been defined in previous studies and are consistent with standard material extraction and manufacturing or construction processes. The use phase components have been excluded in many previous studies due to the challenges in their quantification and the uncertainty in the process (Santero & Horvath, 2011). However, recent studies show that the contribution of use phase could be significant in a comparative life cycle assessment, especially for the high-volume roads due to the effect of pavement vehicle interaction (PVI) (Akbarian et al, 2012; Noshadravan et al, 2013). Two major sources of PVI include fuel losses due to changes in roughness and fuel losses due to deflection of pavements. The LCA model applied in this study accounts for both roughness and deflection components. The deflection losses are calculated based on the model developed by (Akbarian et al, 2012). 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 Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO, 2008). 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 (Zabar & Chatti, 2010). It should be noted that the environmental impact of the use phase is often modeled as a differential effect. In other words, the burden is calculated relative to some appropriate baseline. More details on the description and characterization of use phase components are presented in (Noshadravan et al., 2013).

The life-cycle inventory has been defined by identifying the flow of relevant materials and energy burdens associated with activities. Transportation distances for most materials were obtained from the US Bureau of Transportation Statistics (BTS, 2007), while cement transportation information was calculated from the Portland Cement Association (PCA) environmental surveys (PCA, 2010). Life cycle inventory data for upstream unit processes were obtained from Swiss center for life cycle Inventory (ecoinvent center) (Hischier & Weidema, 2010) and United States life cycle inventory (USLCI) databases (NREL, 2012). Additionally, the environmental impact of cement was calculated using confidential energy and material usage surveys for individual cement plants obtained from the PCA, which enables us to characterize variation in the impacts. The information on the characterization of burden for construction processes, including asphalt and concrete mixing and paving energy, as well as the maintenance energy can be found in (Stripple, 2001; IGGA, 2009).

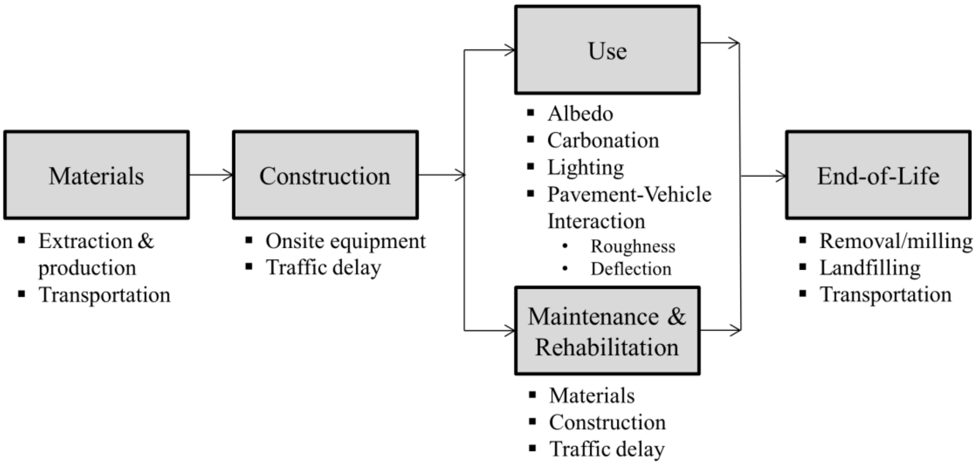

Figure 1 – System boundary for pavement LCA.

For the impact assessment, Global warming potential (GWP) is used and is calculated based on the guidelines put forward by the Intergovernmental Panel on Climate Change (IPCC, 2001). GWP characterizes the relative burden of various environmental emissions in terms of carbon dioxide equivalent. This is only one of many measures of environmental burden. Future studies should consider the extensibility of the conclusions presented here when considering other metrics of burden.

2.2 Uncertainty analysis

LCA is a data-intensive methodology and LCA models depend on many different input parameters. Characterization of these parameters requires information from a large range of sources. There is often uncertainty associated with the data due to inherent variation, measurement inaccuracies, lack of information, or simply human error. Moreover, uncertainty can stem from the quality or appropriateness of the data since in many cases there is a limitation in availability or accessibility of data and the use of proxy data is unavoidable. In order to draw a meaningful conclusion from the results of comparative assessment the uncertainty should be sufficiently taken into account. We conduct a comprehensive uncertainty analysis in our life cycle assessment model to propagate the major sources of uncertainty into the environmental impact. In particular we consider three sources of uncertainty in LCA parameters: measurement uncertainty, application uncertainty, and the model uncertainty in the prediction of roughness. A detailed description of these sources of uncertainty and the characterization are presented elsewhere (Noshadravan et al., 2013) and is briefly reviewed here.

Measurement uncertainty refers to errors due to the inability to precisely measure a value, whether due to human error, improperly calibrated equipment, or inherent variation of the value. We use empirical data whenever available to characterize the statistical distribution of parameters. In the absence of empirical information we use default quantities for measurement uncertainty provided by the ecoinvent guideline (Weidemat et al., 2011). These quantities are categorized by process or material type as well as type of emissions based on expert estimates.

The application uncertainty addresses the appropriateness of the data source used in modelling a quantity of interest. It quantifies the stochastic errors due to the use of other relevant data sources to represent the amount or flow of materials and processes in the system that may or may not be an accurate representation of the data. We make use of data quality indicators established by ecoinvent (Weidemat et al., 2011) to quantify the application uncertainty. In ecoinvent the data quality indicators are based on using a pedigree matrix approach adapted from (Weidema & Wesnas, 1996; Weidema, 1998). Based on this approach the quality of the data is scored with respect to different characteristics and the scores are then translated into quantitative variation.

One of the important contributors of the use phase in the LCA model is the roughness-induced emissions. The prediction of IRI over time is extracted from output of Pavement-ME. There is an underlying probabilistic model associated with the prediction of IRI over time using MEPDG. Although the pavement is designed for a prescribed level of reliability, the uncertainty in the roughness evolution over time can be significant. We account for this uncertainty in our LCA analysis and propagate it into the estimation of roughness-induced emissions in pavement LCA (Noshadravan et al., 2013). Once different sources of uncertainty are characterized, a Monte-Carlo simulation is performed to estimate the uncertainty in the global warming potential of the pavement system as a whole.

2.3 Comparative analysis

Life cycle analysis is often undertaken to compare different products or alternative designs. In a comparative assessment the uncertainty in the difference between two products drives the decision rather than the overall uncertainty in individual products. As such, the comparison needs to be conducted in a relative manner. In order to characterize the relative impact and the associated uncertainty, we represent the relative performance of two alternative designs in terms of a comparison indicator (Huijbregts et al., 2003) that is defined as the ratio between the impact of two designs as follows

$$\mathbf{CI} = \frac{\mathbf{Im}_A}{\mathbf{Im}_B} \tag{1}$$

in which $\mathbf{Im}_A$ and $\mathbf{Im}_B$ are the environmental impact values for designs A and B respectively. It is worth pointing out that in the Monte Carlo simulation of the comparison indicator, the analysis is conducted for both products simultaneously such that the same sample sets are used for the input parameters that are commonly used in life cycle analysis of both alternative designs. Once the samples of $\mathbf{CI}$ are computed, the probability distribution and statistics of this quantity can be estimated. This information can then be used to quantify the relative difference in the performance of two products in a statistical sense. For instance, we can look the probability that the comparison indicator is less than one, that is $\beta = \mathbf{P}(\mathbf{CI} < 1)$ which characterizes the likelihood that design A has lower impact than design B. A decision regarding the superiority of design A over design B can then be made when β is greater than a prescribed threshold.

4. CASE STUDY

For the case study we consider two alternative pavements for an urban interstate highway in Missouri (dry-freeze climatic region). The two alternatives are: a hot-mix asphalt concrete (AC) and a jointed plain portland cement concrete (PCC). In order to study the effect of the analysis period and the design life in pavement LCA, these two alternatives are compared under four different scenarios. These scenarios are defined by prescribing different set of values for the analysis period and the design life, which are presented in Table 1. For each scenario a pair of AC and PCC pavements was designed by an independent design firm. The pairs of alterative designs are considered to be equivalent since they were created under the same set of contextual conditions. The designs and maintenance and rehabilitations schedules have been created by the pavement designer using Pavement-ME software, which implements the calculations specified by MEPDG.

The general specification of designs is detailed in Table 2, while Table 3 describes their maintenance schedules for the various scenarios.

Table 1 – pavement LCA scenarios

Scenarios	Design Life	Analysis Period
Scenario 1	20	50
Scenario 2	30	50
Scenario 3	30	75
Scenario 4	50	100

5. RESULTS

For each scenario and each pavement design under consideration, numerical samples of modeled GWP and the resulting comparison indicator (see Eq. 1) were obtained by performing Monte Carlo simulations. Statistical distributions of these quantities are then estimated from the simulated samples. A statistical characterization based on 10,000 such trials is summarized in this section. These same results are used to estimate the probability density function of $\mathbf{CI}$. The values of $\beta = \mathbf{P}(\mathbf{CI} < 1)$ are also estimated.

The resulting overall GWP and the contribution of different life cycle phases are shown in Figure 2. Each data point in the plot depicts the 5^{th}, 25^{th}, 50^{th} (median), 75^{th}, and 95^{th}, percentile of the values observed. The estimated probability density functions of total GWP are also plotted in Figure 3-(a) and 3-(b) for PCC and AC, respectively. The results indicate that there is relatively higher scatter in the calculated GWP for the case of PCC design. By looking at the contribution of different phases in Figure 2 it can be seen that this behavior is largely driven by the use phase. Further investigation shows that this uncertainty mainly stems from scatter in the prediction of IRI, which is translated into the IRI-induced emissions. The comparison of statistical distributions for scenario 1 and scenario 2 indicates that the uncertainty is not considerably influenced by the choice of design life. However, the longer analysis period can increase the uncertainty in both cases of AC and PCC designs, which is again predominantly driven by the use phase and in particular IRI-induced emissions. It is worth pointing out that the higher uncertainly in IRI-induced global warming potential should not be generalized and attributed to the type of the pavement. The environmental performance of pavements due to the roughness is a design-dependent behavior rather than material characteristics. Relative performance of different pavement types in terms of their IRI-induced emissions significantly depends on the climate scenarios as well as the design features. The scatter in the predictions also varies with these features.

Table 2 – General characteristics of pavement designs

Location		Missouri (wet-freeze climate)
AADT (vehicle/day)		78378
AADTT (vehicle/day)		8000
Number of lanes		6
Lane width (m)		3.60
Paves shoulders		2
Shoulder width (m)		3.60
PCC design	Concrete thickness (mm)	280[a], 292[b], 305[c]
	Dowels diameter (mm)	42
	Crushed stone base thickness (mm)	152
AC design	Asphalt thickness (mm)	343
	Crushed stone base thickness (mm)	610

[a] scenario 1 & 2 [b] scenario 3 [c] scenario 4

Table 3 – Maintenance schedules based on MEPDG for different scenarios

	Year	Activity
		Scenario 1
PCC design	20	6 mm diamond grinding and full depth repair, 0.07% slab replacement
	40	6 mm diamond grinding and full depth repair, 0.02% slab replacement
AC design	20	50 mm mill, 50 mm AC overlay, patching of 0.13% lane area in the travel lane
	37	50 mm mill, 50 mm AC overlay, patching of 0.18% lane area in the travel lane
		Scenario 2
PCC design	30	6 mm diamond grinding and full depth repair, 0.13% slab replacement
AC design	20	50 mm mill, 50 mm AC overlay, patching of 0.13% lane area in the travel lane
	37	50 mm mill, 50 mm AC overlay, patching of 0.18% lane area in the travel lane
		Scenario 3
PCC design	30	6 mm diamond grinding and full depth repair, 0.06% slab replacement
	55	6 mm diamond grinding and full depth repair, 12% slab replacement
	65	6 mm diamond grinding and full depth repair, 17% slab replacement
AC design	20	50 mm mill, 50 mm AC overlay, patching of 0.13% lane area in the travel lane
	37	50 mm mill, 50 mm AC overlay, patching of 0.28% lane area in the travel lane
	50	178 mm mill, 178 mm AC overlay
	63	77 mm mill, 77 mm AC overlay, patching of 0.52% lane area in the travel lane
		Scenario 4
PCC design	40	6 mm diamond grinding and full depth repair, 10% slab replacement
	60	6 mm diamond grinding and full depth repair, 15% slab replacement
	75	6 mm diamond grinding and full depth repair, 20% slab replacement
	90	6 mm diamond grinding and full depth repair, 30% slab replacement
AC design	20	50 mm mill, 50 mm AC overlay, patching of 0.13% lane area in the travel lane
	37	50 mm mill, 50 mm AC overlay, patching of 0.28% lane area in the travel lane
	50	178 mm mill, 178 mm AC overlay
	63	77 mm mill, 77 mm AC overlay, patching of 0.52% lane area in the travel lane
	75	203 mm mill, 203 mm AC overlay
	90	77 mm mill, 102 mm AC overlay, patching of 0.52% lane area in the travel lane

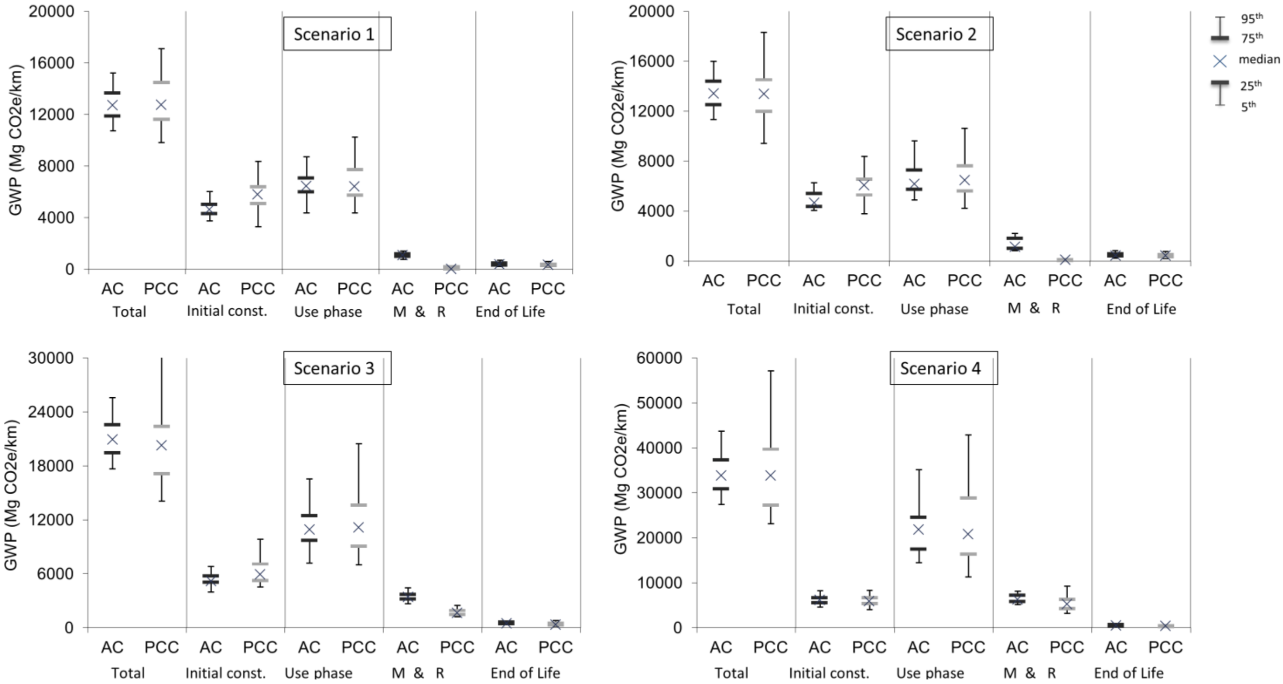

Figure 2 – Comparison of total GWP and the contribution of different phases for AC and PCC design for different scenarios.

The probability density functions of comparison indicator, $\mathbf{CI}$, are estimated and plotted in Figure 3-(c) for each scenario. The corresponding values of β are also reported. It is seen that among these four scenarios, β ranges from 41% for scenario 1 to 63% for scenario 3. Generally speaking, this range of values indicates that the difference in the performance of the given AC and PCC designs in terms of their GWP is not statistically significant for any of the scenarios. Consequently, for the presented case study the variation in the design life and the analysis period does not lead to a different decision regarding the environmental advantage of these two pavement types.

5. CONCLUSIONS

The effect of variation in the design life and the analysis period on the environmental implications of pavements is studied. A life cycle assessment model that takes into account the major sources of parameter uncertainty is developed and used to compare global warming potential of two pavement alternatives under four different scenarios. These scenarios are defined by prescribing different values for the design life and the analysis period of pavements. The two pavement alternatives include a hot-mix asphalt concrete design and a jointed plain Portland cement concrete design in a wet-freeze climatic region. The results indicate that for the presented case study the variation in the design life and the analysis period affects the variation for an individual pavement design but does not lead to a different decision regarding the environmental advantage of these two pavement types. The uncertainty in the assessment of environmental impacts becomes larger as the analysis period increases, which is mainly due to the use phase impact, particularly roughness-induced emissions.

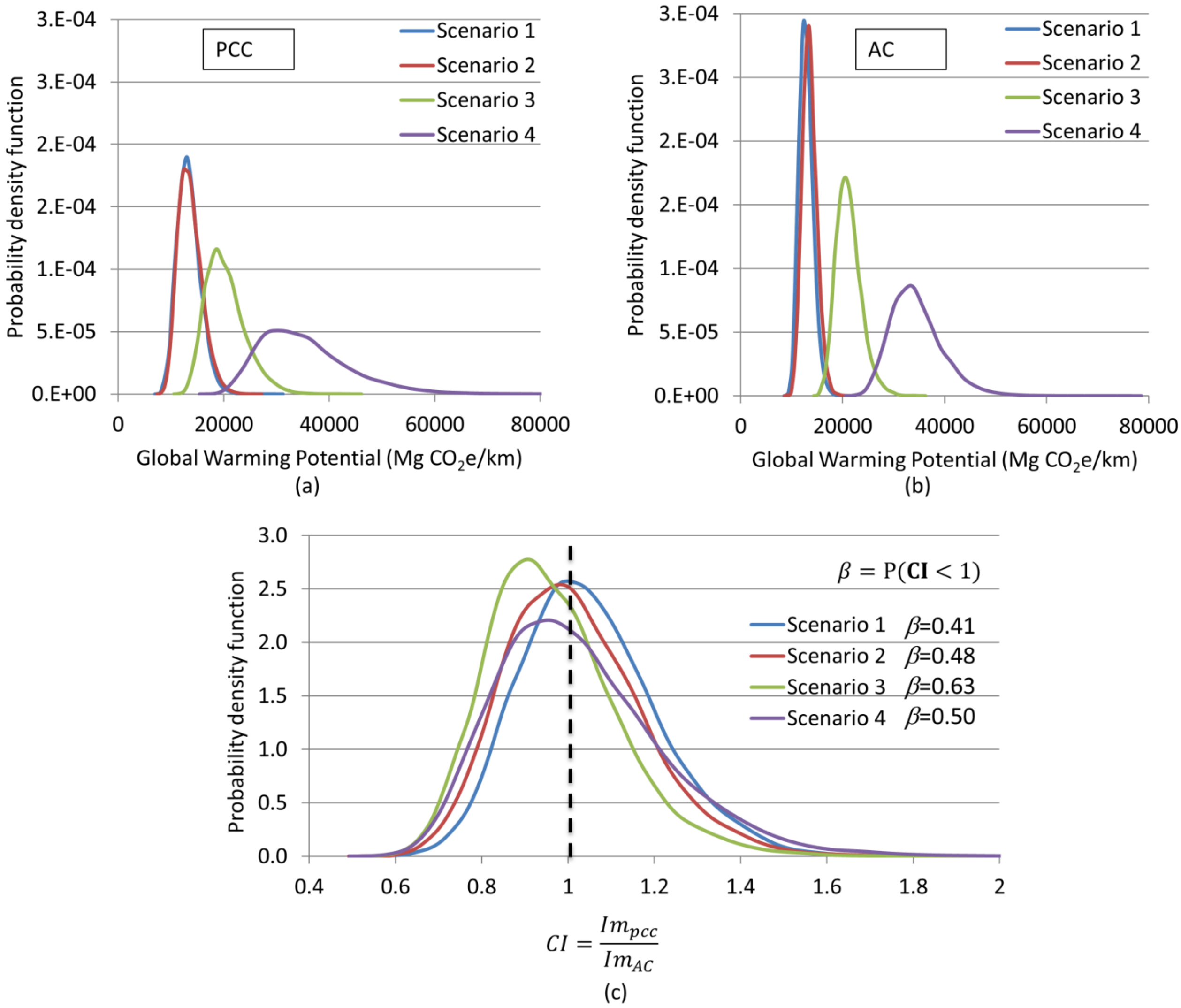

Figure 3 – (a), (b) Estimated probability distribution function of GWP for AC and PCC designs, respectively (c) Probability distribution function of comparison indicators.

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REFERENCES

AASHTO (2008). "Mechanistic-empirical pavement design guide", interim edition: A manual of practice [Computer software manual]. Washingotn, D.C..

Akbarian, M., Moeini-Ardakani, S. S., Ulm, F.-J., & Nazzal, M. (2012). "Mechanistic approach to pavement-vehicle interaction and its impact on life-cycle assessment". Transportation Research Record: Journal of the Transportation Research Board, 2306(1), 171–179.

BTS (2007). "Commodity flow survey". Bureau of Transportation Statistics.

Häkkinen, T., & Mäkelä, K. (1996). “Environmental adaption of concrete: Environmental impact of concrete and asphalt pavements”. VTT Finland: Technical Research Center of Finland. Research Notes 1752.

Hischier, R., & Weidema, B. (2010). “Implementation of life cycle impact assessment methods”. Swiss Centre for Life Cycle Inventories (ecoinvent Centre).

Horvath, A., & Hendrickson, C. (1998). “Comparison of environmental implications of asphalt and steel-reinforced concrete pavements”. Transportation Research Record: Journal of the Transportation Research Board, 1626(1), 105–113.

Huijbregts, M. A., Gilijamse, W., Ragas, A. M., & Reijnders, L. (2003). “Evaluating uncertainty in environmental life-cycle assessment. a case study comparing two insulation options for a dutch one-family dwelling”. Environmental science & technology, 37(11), 2600-8.

IGGA. (2009).” Conserving fuel when rehabilitating concrete roads”. West Coxsackie, NY: International Grooving & Grinding Association.

Meil, J. (2006). “A life cycle perspective on concrete and asphalt roadways: embodied primary energy and global warming potential. Athena Research Institute.

NCHRP. (2004). “Guide for mechanistic-empirical design of new and rehabilitated pavement Structures”. National Cooperative Highway Research Program and Transportation Research Board and National Research Council.

Noshadravan, A., Wildnauer, M., Gregory, J., & Kirchain, R. (2013). “Comparative pavement life cycle assessment with parameter uncertainty”. Transportation Research Part D: Transport and Environment, 25, 131-138.

NREL (2012), U.S. life-cycle inventory database (http://www.nrel.gov/lci/).

PCA (2010). Cement plant profiles. Ed. Portland Cement Association.

Santero, N. J., Harvey, J., & Horvath, A. (2011). “Environmental policy for long-life pavements”. Transportation Research Part D: Transport and Environment, 16(2), 129–136.

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

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

Weidema, B., & Wesnas, M. (1996). “Data quality management for life cycle inventoriesan example of using data quality indicators”. Journal of Cleaner Production, 4(3-4), 167-174.

Weidema, B. P. (1998). “Multi-user test of the data quality matrix for product life cycle inventory Data”. International Journal of Life Cycle Assessment, 3(5), 259-265.

Weidema, B. P., Baucer, C., Hischier, R., Mutel, C., Nemecek, T., Vadenbo, C. O., & Warnet, G. (2011). “Overview and methodology, data quality guideline for the ecoinvent database version 3”. Swiss Centre for Life Cycle Inventories (ecoinvent Centre).

Yu, B., & Lu, Q. (2012). “Life cycle assessment of pavement: Methodology and case study”. Transportation Research Part D: Transport and Environment, 17(5), 380–388.

Zaabar, I., & Chatti, K. (2010). “Calibration of hdm-4 models for estimating the effect of pavement roughness on fuel consumption for U.S. conditions”. Transportation Research Record: Journal of the Transportation Research Board, 2155, 105-116.