Role of Uncertainty Assessment in LCA of Pavements

S.Inti
Department of Civil Engineering, The University of Texas at El Paso, El Paso, TX, USA

M.Sharma
Department of Civil Engineering, The University of Texas at El Paso, El Paso, TX, USA

V.Tandon
Department of Civil Engineering, The University of Texas at El Paso, El Paso, TX, USA

ABSTRACT: Life Cycle Assessment (LCA) is a tool to appraise the environmental impact of a pavement during its service life. Typically, the LCA assessor has to make some assumptions and judgments, employ data from different sources, use analytical tools and models, etc., in order to provide information to the transportation officials for decision making. Since assumptions and data from different sources have inherent uncertainty, it is essential to explicitly report the underlying uncertainties and their consequences in LCA outputs. This study recommends an approach for performing uncertainty assessment in pavement LCA. The first step of the recommended approach is to define a clear objective for the need of the assessment. Then establish the scope of assessment such that it is technically feasible and satisfies the assessment objective. Prioritizing the phases in LCA that influence the output and concentrating only on significant phases makes the uncertainty assessment viable. The next step is classifying the uncertainties that prevailed in prioritized phases. Classification supports in selecting the proper methods and techniques that can apprehend the uncertainty. Finally, present the uncertainty results clearly and effectively to the transportation officials. The recommended approach is demonstrated through an example.

1 INTRODUCTION

Life Cycle Assessment (LCA) tool has gained popularity in the pavement infrastructure because it comprehensively quantifies the emissions and energy flows of pavement in its service life. The output from LCA helps decision makers in choosing a design and/or material and/or construction practice, etc. to lessen the burden on the environment. The practitioners of LCA employ the guiding principles provided by various standards such as International Organization of Standardization (ISO) 14040 (2006), ISO 14044(2006), Environmental Protection Agency (EPA) document (Scientific Applications International Corporation (SAIC) 2006), etc. However, there is no US government authorized guidelines for performing LCA of pavement (U.S. Department of Transportation, Federal Highway Administration (FHWA) 2014). Additionally, lack of a comprehensive and official database for the construction of pavements impacts the reliability of LCA.

Various researchers (Nisbet et al. (2000), Mroueh (2000),Huang et al. (2009), Weiland and Muench (2010), Santero et al. (2011), Tatari et al. (2012), Vidal et al. (2013), Barandica et al. (2013), Liu et al. (2014), Thiel and Len (2014), Anastasiou et al. (2015)), have performed LCA of pavements using available tools and guidelines. These researchers attempted to perform a comprehensive assessment by making some assumptions, using models that were not exclusively developed for pavement LCA, employ data from other geographical location or technology, etc. These factors lead to uncertainty in LCA output at different phases. The existence of uncertainty is also acknowledged in the ISO standards. It is stated in ISO 14040 (2006) that "*LCA does not predict absolute or precise environmental impacts due to the inherent uncertainty in modeling of environmental impacts.*" LCA assessors need to focus on either reducing the uncertainty or develop an effective way of communicating the consequences of uncertainty (e.g., assumptions) in the assessment to transportation officials.

2 LITERATURE REVIEW

It is important to understand the true sense of uncertainty. Heijungs and Huijbregts (2004) stated that the uncertainty arises by using data that is inappropriate, unreliable, or possess some degree of inherent variability. Weidema et al. (2013) expressed uncertainty as any distribution of data within a population either caused by random variation or bias. The chances are high that every LCA assessor encounters certain type of uncertainty. Knowing the fact that uncertainty subsists in LCA, the questions that arise are:

1) what is the credibility of the LCA results? (Allaire and Willcox 2014), 2) which part of the LCA processes leads to primary uncertainty? (Hung and Ma 2009) , 3) How to present the uncertainty in LCA that can be easily comprehended by the policy makers?

A systematic uncertainty assessment answers to the above questions to a good extent. According to Baker and Lepech (2009), uncertainty assessment supports:

a) better decision-making
b) increases transparency in the data
c) increases the quality of analysis, and
d) helps in planning information gathering exercise(s).

May and Brennan (2003), and Helton et al. (2006) described that the uncertainty analysis could provide a possible range of outcomes rather than single outcome based on the individual data uncertainties. It is important to understand various chief sources of uncertainty and the best techniques to handle them.

2.1 *Sources of Uncertainty in LCA*

Baker and Lepech (2009) classified the uncertainties as below:

- Database uncertainty (missing or unrepresentative data)
- Model uncertainty
- Statistical measurement error (data based on a limited set of sample)
- Uncertainty in preferences (uncertainty due to analyst's choices)
- Uncertainty in a future physical system, about the currently designed system (the degree to which the future conditions change in which present design will be subjected)

One can further classify these uncertainty sources, for example, database uncertainty can be due to outdated data, spatial or technological variability of available data, inconsistency between various available data sources, etc.

2.2 *Handling Uncertainty*

Typically, the objective of uncertainty assessment can be either reducing the uncertainty or communicating the possible impacts of uncertainties on LCA outputs. If the focus is reducing the uncertainty, Heijungs and Huijbregts (2004) clearly mentioned three approaches:

1) Scientific Approach: Performing thorough research while developing the characterization models, increasing the data size, etc.
2) Constructivist Approach: Involving stakeholders, discussing and finally deciding on or voting for a consensus characterization factors.
3) Legal Approach: Relying on authoritative bodies reports, like ISO or the US EPA.

Out of the three ways, the first two are not practical at the level of an analyst because it needs the involvement of state or governmental bodies. Therefore, the analysts often attempt in using the data from authoritative bodies like the US EPA, the FHWA, etc. Additionally, some researchers have suggested handling uncertainty by using local databases containing site specific data (Cellura et al. 2011).

However, most attention in the published literature of uncertainty assessment in LCA of pavements is given in communicating the possible outcomes due to the variability in inputs or data quality. There are various analytical tools such as a first order approximation of the Taylor expansion of the underlying model, fuzzy set methods, neural networks, etc., but the principal tool employed is Monte Carlo Simulation (MCS) (Hung and Ma 2009) (Noshadravan et al. 2013) (Allaire and Willcox 2014) (Yu et al. 2016) followed by sensitivity analysis.

In MCS, the input parameter is expressed in the form of a probability distribution. Multiple simulations can be performed by varying the input parameters (as per probability distributions), and outputs can be collected for each simulation. From the pool of outputs obtained, statistical properties can be evaluated, and the possible outcomes are presented. The principal challenge in using MCS is assigning a probability distribution and defining statistical input parameters. Most common type of probability distributions employed are the normal, lognormal, uniform, and triangular (May and Brennan 2003), (Heijungs and Huijbregts 2004).

In general, if the experimental data is not available, the LCA analyst assumes the probability distribution and statistical parameters (variance, standard deviation, etc.) for performing MCS. In some cases, if the input LCA data is available from numerous sources or from different time periods etc., then the analyst can characterize the quality of the available data and develop the statistical parameters for performing simulations. The data quality indicators (DQI's) approach developed by Weidema and Wesnes (1996) is a well-known method for data characterization. The data is characterized based on five parameters that are reliability, completeness, temporal correlation, geographical correlation, and technological correlation. A numerical score is assigned to each parameter, and an aggregated DQI score is estimated at the end. Data quality score can be converted into a probability distribution function or as an additional variance in the data. For example, Yu et al. (2016) employed DQI score to develop a modified beta distribution based on the works of Canter et al. (2002). Noshadravan et al. (2013) used DQI's scores to calculate the additional variance to the data as per the procedure presented in Weidema et al. (2013). Similar to MCS, sensitivity analysis, scenario analysis are other tools that can be used to include uncertainty assessment in LCA.

Previous studies employed uncertainty propagation tools for a particular input parameter or a single phase of LCA. For example, Yu et al.(2016) worked on the albedo effect of pavements, another study by Yu et al.(2016) presented a procedure to evaluate the data quality of inputs for asphalt layers in pavement construction, Noshadravan et al. (2013) accounted for the uncertainty in the prediction of pavement roughness. There is a lack of guidance for performing the overall uncertainty assessment for LCA of pavements. The efforts from the previous researchers are commendable; the employed methodologies and findings from their studies can be implemented in performing a comprehensive and systematic uncertainty assessment of LCA of pavements.

3 OBJECTIVE

The objectives of this study are to recommend a suitable approach for performing uncertainty assessment in LCA of pavements, and to demonstrate the proposed approach through an example.

4 PROPOSED APPROACH

This study proposes an approach which comprises of four basic parts

1) Goal of uncertainty assessment
2) Prioritization of major influencing emission sources
3) Classification of uncertainty and selection of uncertainty propagating or mitigating tools
4) Presentation of results

4.1 *Goal of uncertainty assessment*

The necessity of conducting uncertainty assessment needs to be clearly defined. The goal of assessment influences the whole assessment and helps in outlining the scope.

4.2 *Prioritization of major influencing emission sources*

After defining the goal, the next step is to choose a well-outlined approach performing the assessment. Uncertainty may happen at every phase of LCA. Even though performing uncertainty assessment at every phase is desirable, it may be neither practical nor necessary. Heijungs and Huijbregts (2004) cautioned about the darker sides of uncertainty assessment. Incorporating uncertainty assessment makes LCA a more tedious practice because additional efforts are required for data collection. Employing various assessment techniques on all uncertainty sources generates a swarm of results which may overshadow the LCA itself. Often too much information leads to pessimism. Therefore, the uncertainty assessment needs to strike a balance between the practicality to analysts and meaningfulness to transportation officials.

Prioritization helps in maintaining the desired balance. A feasible scope for the uncertainty assessments can be attained by prioritizing assessment only on the phases which significantly impact the overall LCA results, and on the judgments or assumptions made by analysts, which affect the LCA outputs or decisions.

4.3 *Classification of uncertainty sources*

Once the key phases are prioritized the next step is to classify the uncertainty existed in these phases. Classifying uncertainty supports in identifying the tools and techniques required to propagate or lessen the uncertainty, as each source of uncertainty needs to deal with an appropriate approach. Figure 1 shows the primary sources of uncertainty in each phase of LCA and the possible actions that can be implemented to mitigate or propagate the uncertainty.

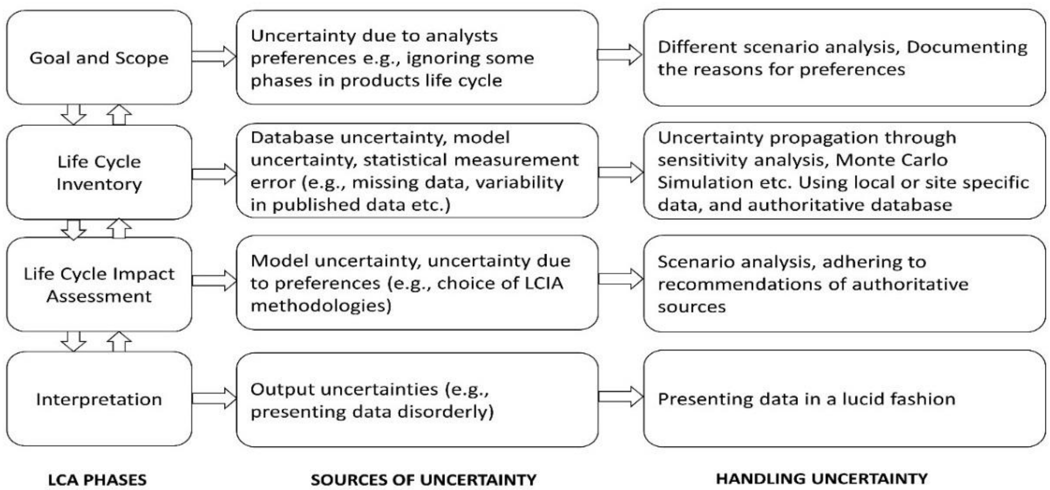

Figure 1. Sources of uncertainty and handling it at various phases of LCA

4.4 *Presentation of Results*

Since uncertainty assessment involves complicated calculation techniques like simulations, statistics, etc., the output may overwhelm the policy or decision maker. Therefore, it is essential that the results are presented in a lucid fashion that strengthens the understanding of risks in LCA and helps in decision making.

5 EXAMPLE

Three equally performing pavement designs are analyzed using Mechanistic-Empirical Pavement Design for 30 years of El Paso Texas climate conditions are shown in Figure 2. Type of pavement layers, thicknesses, and year of maintenance are also mentioned in Figure 2. Each design is a six-lane highway (three lanes on each side) for an annual average daily traffic (AADT) of 60,000 at a growth rate of 0.75.Ten percent of the traffic comprises of trucks. The performance of each pavement for 30 years are assessed using the pavement design software.

Initially, LCA is performed to evaluate the environmental impacts due to each pavement design. Global warming potential (GWP) was estimated for the three designs for a one-mile length of the highway for 30 years. Five segments (material extraction, transportation, construction, use, and maintenance) of a pavement life cycle are considered in the GWP estimation. The elements considered in each segment, the models and data sources employed, and the assumptions made in the GWP estimation are shown in Table 1. For instance, during usage segment of pavement, emissions due to combustion of gasoline and diesel, and tire wear are considered. Other emission sources during highway usage like albedo, carbonation, and lighting are not considered because they are more beneficial when one compares an asphalt and concrete top surfaces (In this case study all designs have asphalt surface on top). The end of life of the pavements is not considered in LCA because as there is no well-defined end of life where the pavement would be demolished and thrown away (Weiland and Muench 2010).

The estimated GWP of three designs is summarized in Figure 3. The results suggest that the Design 3 has the lowest GWP compared to Designs 1 and 2. Design 3 bettered Design 1 and Design 2 by 6259, 8432 tons of GWP per mile of highway. However, by closely examining the models, data sources, and assumptions in the GWP estimate and associating them with types of uncertainty portrayed in Figure 1, it is evident that there is certain riskiness in the estimate. For example, the material extraction includes data from different geographical locations (Tire LCA from Japan, Asphalt production emissions from Europe, etc.,), construction phase has limited sample sizes (construction equipment data), transportation and maintenance phases have some critical assumptions (future maintenance timing 9AM-5 PM), and use phase has modeling errors (an average passenger car emissions used for estimating overall emissions).

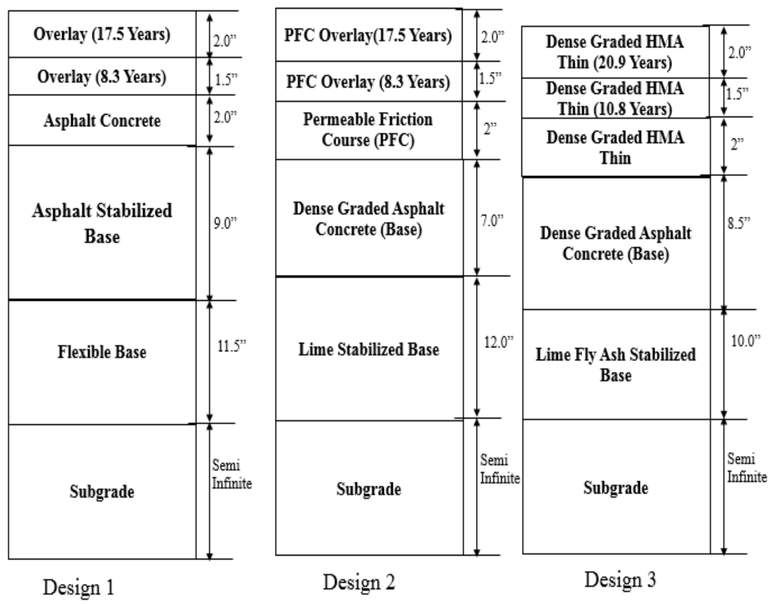

Figure 2. Pavement Sections

5.1 *Uncertainty Assessment*

Since uncertainty persists in the assessment, explicitly presenting the influence of uncertainty enhances the transparency of LCA and increases the confidence in decision making. In order to perform an uncertainty assessment on this example, the approach explained in the previous section is employed.

5.1.1 *Goal of uncertainty assessment*

The main goal of this assessment is to evaluate the influence of variation in input data quality and assumptions made in the LCA and finally present the range GWP for the three designs.

5.1.2 *Prioritization of major influencing emission sources*

The most affecting sections of pavement life cycle on the overall GWP need to be categorized. It is apparent from the LCA results in Figure 3 that the emissions from vehicles during highway usage, predominantly (90% of total GWP) impacts the overall LCA followed by the traffic delay emissions (9%) during maintenance of the highway. Close to 70 % of the GWP difference between Design 1 and Design 3 can be attributed to use and maintenance phases, and in the case of Design 3 and Design 2, the percentage is around 98 %. Hence, use and maintenance phases can be considered as a priority for uncertainty assessments as they are driving the overall LCA and the decision.

Table 1. Data Sources for Life Cycle Inventory

Phase	Model Used	Data Sources	Assumptions
Material Production	Customized emissions model are developed using Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) (Argonne GREET Model).	Asphalt: Life Cycle Inventory Bitumen (Blomberg et al. 2011), Aggregate: Greenhouse Gas Emissions Inventory CEMEX Jesse Morrow Mountain Plant (Downey 2009), Asphalt Plant Operations: Hot Mix Asphalt Plants Emission Assessment Report (US EPA 2000) (Myers et al. 2000), Emulsion: Life Cycle Inventory Emulsion (Blomberg et. al. 2011), Fuel Combustion factors: Emissions Factors & AP42.	The mix designs for materials like asphalt concrete; lime stabilized base were considered as per Texas commonly used proportions.
Transportation	Customized emissions model are developed using Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET).	A 20-ton capacity truck with full front haul and empty backhaul is assumed with fuel (diesel) consumption of 5.3 miles per gallon. Diesel is considered as the fuel used in trucks for transporting materials.	Transportation distance of raw materials like (asphalt, lime, etc.,) to plant or construction site 50 miles and 12 miles considered as the distance between asphalt plants to the construction site.
Construction	The emissions during construction from equipment and machinery were estimated using NONROAD 2008 database.	The type of construction equipment and working durations are estimated by using RSMEANS 2012. The equipment details were taken from common construction equipment manufacturers like Caterpillar, Dynapac, Bomag, Roadtech, Wirtgen, etc. The emissions data for equipment (machinery) available in NONROAD 2008 is matched with construction equipment by horsepower.	After estimating the emissions from each equipment per hour, the total impacts is calculated by multiplying machinery hours required for activity (i.e. asphalt concrete) and time efficiency.
Use	Models reported in NCHRP 720 for estimating vehicle operating costs were used to calculate the gasoline and diesel consumption, and tire wear.	Tire: Typical tire manufacturing LCA is developed by using Life Cycle Assessment of a Car Tire Continental (Kromer et al.), Emission Factor Documentation for AP-42 Manufacture of Rubber Products, Tyre $LCCO_2$ Calculation Guidelines. Emissions from Cars**:** Greenhouse Gas Emissions from a Typical Passenger Vehicle. Emissions from Trucks: Developed emissions from a truck with varying mileage using GREET.	The emissions for manufacturing a passenger car is estimated first, and later the emissions for trucks are estimated based on the proportions of materials used in manufacturing truck and a passenger car tire.
Maintenance	For materials production and transportation, the methods explained above are followed. For estimating the emissions due to traffic delays during maintenance is estimated using Motor Vehicle Emission Simulator.	For traffic delay emissions method proposed by Inti et al. 2016) is employed which used MOVES.	Traffic delay emissions depend on the timing of maintenance and in this study we considered maintenance from 9AM-5PM by closing one lane because this working time has a maximum impact on the environment.

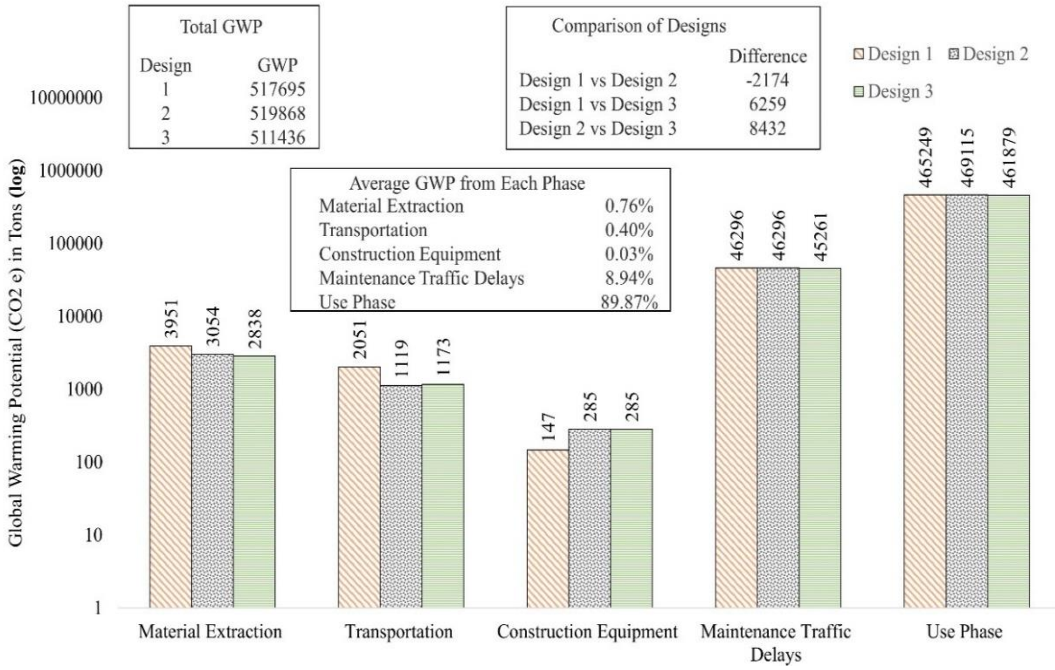

Figure 3. GWP of Three Pavement Designs (Deterministic Approach)

5.1.3 *Classification of uncertainty and selection of uncertainty propagating or mitigating tools*

Use Phase: Vehicle emissions, tire wear related to pavement-vehicle interaction are considered in the use phase of LCA in this study. Vehicle emissions and tire wear are a function of International Roughness Index (IRI) (a pavement distress). The performance of each pavement design is different and yields a distinct IRI. In the initial GWP estimate, the models suggested (for estimating user costs) in NCHRP Report 720 are used. These models were calibrated using vehicles driven on roads of the known condition in the US.

The IRI of the pavement, vehicle type, speed of the vehicles, etc., are the key input to these models. In the initial estimate, the speed of vehicles was considered as 55 miles per hour (MPH) and calculated the emissions based on the IRI generated by pavement design software for three designs. Primarily, the mileage for different vehicles (cars, trucks, vans, etc.) were estimated at 55 MPH and later fuel consumed to travel one mile. Emissions were estimated based on the combustion of a gallon fuel (diesel and gasoline) for a typical passenger and trucks from the US EPA. The software estimated the IRI on an average monthly basis for 30 years. The emissions were estimated for a single day of the month and multiplied it by the total days in a month. The results in Figure 3 were the aggregated emissions for 30 years. Increasing IRI wears the tire quickly, resulting in a frequent change of tires than anticipated. Pavements with poor performance (higher IRI) causes more damage to tires and more emissions due to frequent tire replacement. For tire wear, the LCA of a typical passenger car tire is taken from the Continental Tire manufacturers of the Japan and integrated them with AP 42 emissions for rubber products of the US EPA.

There are various sources of uncertainty in the use phase estimate such as:

- Uncertainty in the model: NCHRP 720 models were calibrated at a geographical location which is different from the current location of study (climate variability)
- Uncertainty in assumptions: Speed of all vehicles for thirty years assumed as 55 MPH
- Uncertainty in the data sources: Tire emissions inventory from a different geographical location (the Japan), fuel consumption emission factors were taken from a typical car and truck in the US.

The impact of climate variability on NCHRP 720 models is not considered in this study. As calibrating the models through field tests in El Paso region (geographical location of the case study) is beyond the scope of this study. However, for another type of uncertainties (vehicle speed, tire emissions, car and truck emission factors), this study used MCS to present the possible range of emissions.

Due to the lack of guidance in choosing the probability distribution functions and parameters from an authoritative body for LCA of pavement, this study assumed probability distributions based on the works of May and Brennan (2003), Heijungs and Huijbregts (2004) and the author's experience. The following probability distributions and parameters are assumed : The speed of vehicles from 30-70 MPH (triangular probability distribution), ten percent variance in the fuel consumption of passenger car and trucks (normal probability distribution, and additional variance (geographical variation) was estimated in the tire emissions using the DQI's method as explained by Weidema et al. (2013) (used lognormal probability distribution). MCS with Latin Hypercube sampling method is used to run 20000 simulations for each design varying these input parameters (results discussed in a later section).

Maintenance Phase (Traffic Delay Emissions): The traffic delay emissions, during maintenance (additional fuel consumption), were estimated as per the procedure explained by Inti et al. (2016). This procedure uses the Motor Vehicle Emissions Simulator (MOVES 2014) and the FHWA's life cycle cost analysis method. Initially, a sensitivity analysis is performed on the various input parameters. It is observed that the major influencing parameter in this procedure is the maintenance timing and maintenance strategies (number of lanes open for traffic during maintenance). These two parameters greatly overwhelm the influence of other inputs. This study performed the scenario analysis as an uncertainty assessment by varying the maintenance timing.

5.2 *Presentation of Results*

Use Phase: Figure 4 shows the results from MCS employed for the use phase uncertainty assessment. Figure 4a displays the cumulative probability distribution of three designs. Even though there is a difference between the three designs in Figure 4a, it is not easily noticeable, and it is hard to interpret such data. Since the designs are being compared, the results from MCS can be presented as shown in Figure 4b. The results indicated that Design 3 performs better than the other two designs and it generates less GWP during use phase at all input combinations. Design 3 excels Design 1 by a range of 2194-4907 (mean 3320) and Design 2 by 4737-10627 (mean 7181) tons of GWP at a probability of 0.9. This type of analysis gives confidence to evaluators as well as to policy makers that their decisions are based on sound assessments. The results also indicated that the speed of vehicles is the critical input factor, which influences the overall use phase emissions.

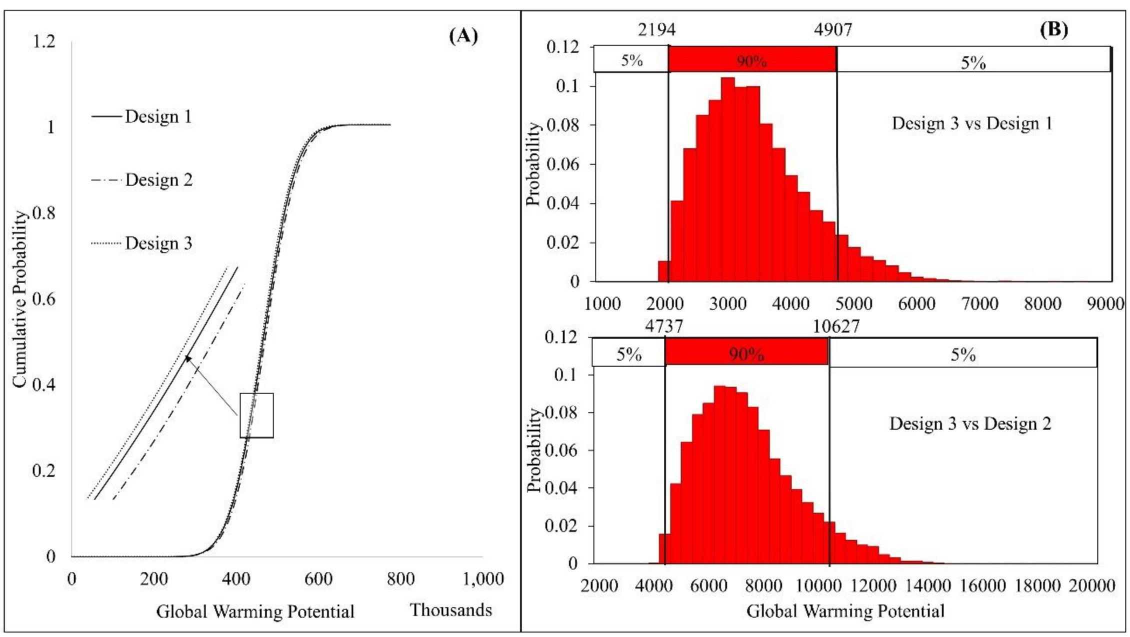

Figure 4. Monte Carlo Simulation Results for Use Phase

Maintenance Phase: The results of scenario analysis are portrayed in Table 2. It is observed that maintenance timing influences the emissions predominantly. Maintenance during nonpeak hours produced fewer emissions and the difference from the three pavements is negligible, and the situation is vice versa if maintenance happens during peak hours of traffic. Design 3 produced lowest GWP than the other designs when maintenance happens during the peak hours of traffic. This analysis shows that the LCA analyst's need a guidance of maintenance practices that the local and state bodies adapt on a regular basis. This type of scenario analysis is required for the phases which are very sensitive to the preferences of LCA analyst.

It is very clear from the two uncertainty analyses that the Design 3 is the one which causes lesser environmental impacts compared to the other designs. The uncertainty assessment bolsters the findings from an initial estimate that Design 3 generates lowest GWP than the other designs.

Table 2. Scenario Analysis (Maintenance Timing) for Traffic Delay Emissions

Maintenance Timing	Number of maintenance hours per day	GWP (1000 Tons)		
		Design 1	Design 2	Design 3
9AM-5PM	8	46.30	46.30	45.26
10PM-6AM	8	0.01	0.01	0.03
11AM-3PM & 8PM-12AM	8	12.23	12.23	12.44
8AM-8PM	12	86.11	86.65	71.43
24 Hours	24	61.57	61.96	51.08

6 CONCLUSIONS AND LIMITATIONS

Uncertainty dwells at all phases of LCA, and there is a need to incorporate the uncertainty assessment to increase the transparency in LCA. Uncertainty assessment displays the possible range of outcomes and the risk involved in the LCA. This study proposed an approach for conducting uncertainty assessment by emphasizing on key steps like prioritization, classification, selection of uncertainty propagating or mitigating methods, and presentation of outputs. The sources of the uncertainty are numerous and addressing every type of uncertainty is not practical. Prioritization directs the uncertainty assessment to focus on the critical phases of pavements life cycle and aids in keeping the scope of the assessment feasible. Classification of uncertainties helps in understanding the type of uncertainties prevailed in the LCA and guides in choosing an appropriate uncertainty appraising method. The presentation of uncertainty results is equally important, as they need to be presented in an understandable way.

A fictional example (three pavement designs) is presented to demonstrate the proposed approach. An initial estimate of GWP for three pavement designs is performed. The initial estimate shows that the Design 3 generated lower GWP than other designs. Use phase of pavement and maintenance traffic delay emissions contributed to the maximum GWP for three designs. So, uncertainty assessment is performed on these two phases by identifying the type of uncertainties. This study used different uncertainty propagation tools like Monte Carlo simulation, data quality index, sensitivity analysis, and scenario analysis. The MCS results for use phase indicates that Design 3 is better than the other two designs at all possible variation in inputs. The simulation results support the findings of the initial estimate. Sensitivity and scenario analysis were performed on the emissions due to traffic delay during maintenance. It is observed that the timing of maintenance and maintenance strategy greatly influences the emissions. If the maintenance happens during non-peak traffic hours, then the difference between the three designs is negligible, and if it happens during peak traffic hours, then Design 3 generated the lowest GWP.

The case study is used just like a numerical example but not to state the best design explicitly. In the case study, we presented only the uncertainty assessment related to input data for the models. A future study is required on handling the uncertainty in the models. Similarly, a future study is needed to include the uncertainty assessments for the other phases of LCA such as life cycle impact assessment.

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