Life Cycle Assessment of Pavements under a Changing Climate

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ABSTRACT: Each of pavements' life cycle phases such as material extraction, transportation, construction, operation, rehabilitation, and end-of-life emits greenhouse gases. Such emissions can be influenced by climate change via changes in the rates of pavement deterioration and thus intensity and frequency of maintenance and rehabilitation. However, climate change has not been given full considerations in previous pavement life cycle assessments (LCA). This research introduced a methodology to integrate the effects of climate change within pavement LCA. A case study was performed to calculate the life cycle global warming potential (GWP) and costs of several typical interstate pavements due to climate change, using downscaled climate data obtained from the Coupled-Model Intercomparison Project Phase 5 (CMIP5). Pavement performance (roughness) was determined using the Pavement ME system. Rehabilitaiton alternatives were also assessed according to predefined pavement roughness triggers. Whereby, roughness triggers were alternatives assessed using LCA. Use of Reclaimed Asphalt Pavement (RAP) was evaluated as an alternative of local virgin materials. SimaPro and PaLATE were used to convert material and energy consumptions into GWP values and equations from HDM4 model were used for determining operational GWP impacts and costs. Asphalt mix production costs were used on the basis of values obtained from local asphalt contractor. For each of the case study scenario, LCA was conducted using historic climatic data, as the current state of practice in field of pavement LCA, as well as future climatic projections. The results of this research demonstrate the importance of considering future climate change in pavement LCAs. This study also presents a generalizable framework for climate change informed pavement LCAs.

1 INTRODUCTION

Over the last decade, life cycle assessment (LCA) has been increasingly applied to quantify the cradle-to-grave environmental impacts of pavements (For example, Santero et al. 2011, Harvey et al. 2014, Huang and Parry 2014). The life cycle of a pavement typically consists of five phases, including materials extraction and production, construction, use, maintenance and end-of-life disposal (FHWA 2016). There is a dynamic interaction between climate and pavements. On one hand, pavements' life cycle generates a large amount of greenhouse gas (GHG) emissions, which calls for a comprehensive understanding of emissions associated with each phase to guide future pavement design and management (Santero 2009). On the other hand, climate change may accelerate pavement deterioration (Mills et al. 2009) and increase its life cycle GHG emissions, energy use, and costs (Qiao et al. 2015). Current pavement LCA methodology typically assumes static climate, which may not be suitable for long-term planning into the future. Hence, it is important to incorporate climate change into pavement LCA in order to improve our understandings on the coupled effects and to provide more reliable results.

Climate change refers to changes in climate stressors in the future, such as increases in temperature, precipitation, and extreme weather e.g. hurricane and flooding (Meyer et al. 2013). For flexible pavements, climate stressors such as temperature, precipitation, wind speed, solar radiation, and groundwater table can be influential to pavement performance and thus changes in these stressors may result in changes of pavement performance and service lives. Previous research found that temperature is the most influential climate stressors (Qiao et al, 2013) and therefore downscaled future temperature was obtained to represent future climate and applied as an input for pavement responses.

The overall goal of this research is to develop a method to incorporate climate change in pavement LCA, using a segment of Interstate-95 (I-95) located in southern New Hampshire as a case study.

2 METHODOLOGY

This study started with identifying a typical road section on I-95 and collecting its structural data. Pavement deterioration was modeled using pavement ME (AASHTO, 2016). In order to assess the effects of climate change on road performance, the default climate data embedded in Pavement ME (hourly data of air temperature, rainfall, humidity, percent of sunshine and groundwater table) were modified based on downscaled daily temperature and precipitation (for the period of 2020-2040) obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) using RCP 4.5 scenario. International Roughness Index (IRI) was adopted as performance criteria of the road section, which can trigger maintenance at certain levels. It is also related to user fuel consumptions (NCHRP 1985, Ockwell 1999, Greenwood and Christopher 2003). The life cycle road performance was incorporated in an attributional LCA to calculate and compare the global warming potential (GWP) and energy consumptions of different pavement structures (see Table 1), with different maintenance regimes over a design life of 20 years. The LCA was conducted using SimaPro (for the production, transportation machinery operation and maintenance phases) and PaLATE (for the construction phase) software. A methodology flowchart is shown in Figure 1. Particularly, two scenarios were considered for road M & R, including a “do nothing” and a mill & fill regime. The mill & fill is applied by milling top 3-inch asphalt layers and fill with a new asphalt layer, which is typically applied in New Hampshire. As a responsive strategy, the triggers were set at IRI of 120, 140, 160, 180, and 200 inch/mile respectively for comparison purposes. The analysis period was assumed to be 60 years to show the average effects of maintenance cycles to the LCA results. In the end, the life cycle GHG emissions and costs of the investigated road segment were estimated.

2.1 *Pavement sections*

An eighteen-mile roadway of I-95 was studied. Four typical pavement structures were identified and applied in the case study, including a standard (baseline), medium strength, deep strength, and full depth structures (see in Table 1). For each structure, three types of asphalt mixtures were investigated: virgin asphalt mixture, virgin mixture with 40% RAP, and 40% RAP for all asphalt layers (see in Table 1). RAP is an alternative to virgin aggregates in hot-mix asphalt (HMA) production and in the construction of base or subbase (Yang 2014).

Material properties inputs for the granular base, sand subbase, and clay subgrade were all assumed to be the default values available in Pavement ME Design. The asphalt material properties including density, air void, binder contents, and dynamic modulus were taken from lab measurements. These properties are used to differentiate long-term performance between virgin binder and RAP. The dynamic modulus inputs are at a higher detailed calibration level and thus likely leads to more accurate performance prediction. It should however be noted that the distress predictions here are made using national calibrations and not regional or local calibrations.

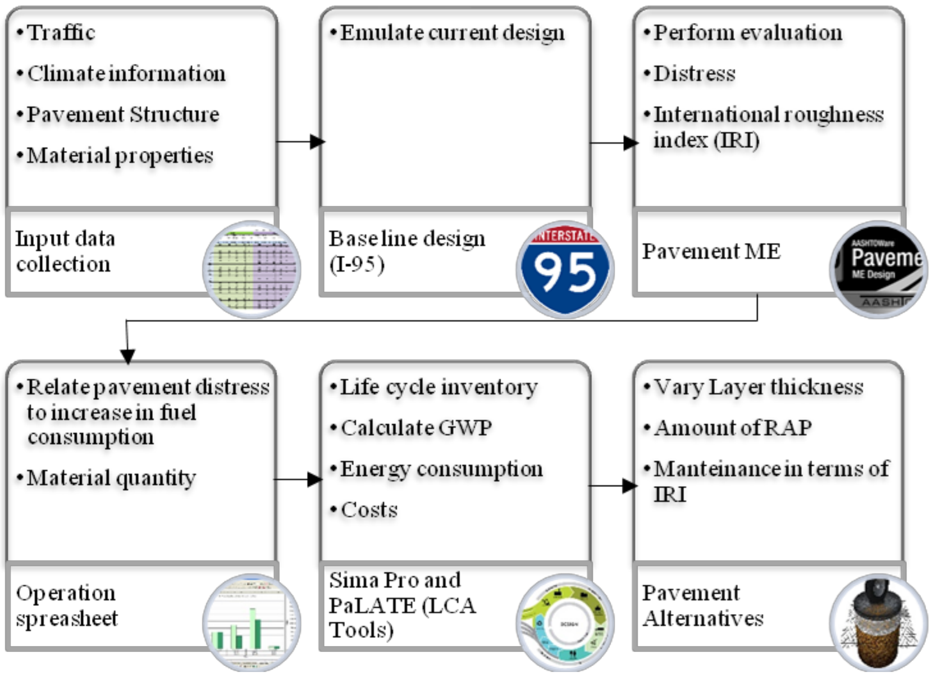

Figure 1 Methodology flowchart

Table 1 Pavement Structures

Structures	All Virgin mixture (V)	Virgin mixture with 40% percent RAP (V/R)	All RAP (R)
Standard	AC: 6 inch GB: 28 inch SB: 8 inch SG: clay	AC: 6 inch GB: 28 inch SB: 8 inch SG: clay	AC: 6 inch GB: 28 inch SB: 8 inch SG: clay
Medium Strength	AC: 9 inch GB: 18 inch SB: 8 inch SG: clay	AC: 9 inch GB: 18 inch SB: 8 inch SG: clay	AC: 9 inch GB: 18 inch SB: 8 inch SG: clay
Deep Strength	AC: 12 inch GB: 12 inch SB: 8 inch SG: clay	AC: 12 inch GB: 12 inch SB: 8 inch SG: clay	AC: 12 inch GB: 12 inch SB: 8 inch SG: clay
Full depth	AC: 16 inch SB: 8 inch SG: clay	AC: 16 inch SB: 8 inch, sand SG: clay	AC: 16 inch SB: 8 inch SG: clay

Note: AC: asphalt concrete, GB: granular base, SB: sub base, SG: subgrade (1 inch = 25.4 mm).

Traffic information was shown in Table 2. Traffic growth was assumed to be 0% as to derive the differences in emissions and costs caused by climate change alone.

Table 2 Traffic Inputs

Input	Value	Source
AADT	88,000	NHDOT Traffic Counts
Percent Trucks	10%	NHDOT Traffic Counts
Operational speed	70 mph (112 km/h)	Default
Percent trucks in design lane	95%	Default

2.2 *Climate*

Climate inputs of Pavement ME are hourly data including temperature, precipitation, wind speed, percent sunshine, and ground water level. As the CMIP5 can only provide daily climatic data, an hourly temperature generator was developed. The generator assumed that the daily minimum temperature (t_{min}) occurs at the sunrise and the maximum temperature (t_{max}) occurs at 2 p.m. in the afternoon. This method was initially presented by De Wit et al. (1978) and was obtained from the subroutine WAVE in ROOTSIMU V4.0 by Hoogenboom and Huck (1986). This method requires t_{min} of the next day and divides the day into two segments, from sunrise to 2 p.m. and from 2 p.m. to sunrise of the next day. The intervening temperatures are calculated from the following equations:

for 0:00 < h < rise and 14:00 < h < 24:00,

$$T(h)=t_{ave}+amp\ (\cos(\pi \times h')/(10+rise)) \quad (1)$$

for rise < h < 14:00,

$$T(h)=t_{ave}-amp\ (\cos(\pi(h'-rise)/(14-rise))) \quad (2)$$

where

$$h' = h + 10 \quad \text{if } h < rise \quad (3)$$

$$h' = 14 \quad \text{if } h > 14 \quad (4)$$

Where rise = time of sunrise in hours; T(h) = temperature at any hour; h = time in hours, h' = h + 10 if h < rise, h' = 14:00 if h > 14:00; $t_{ave} = (t_{min} + t_{max})/2$; amp = $(t_{max} - t_{min})/2$. Daily precipitation was assumed to have occurred on a random hour of each rainy day. Other climatic factors were kept unchanged. For wind speed and sunshine percentage, it is usually considered that they do not dominate pavement performance e.g. IRI and thus their effects are negligible (Qiao et al. 2013). IRI is the most sensitive to temperature and thus it is important to include its impact. Changes in groundwater level may also be influential for IRI in some cases, especially for thin asphalt (Qiao et al. 2013). However, groundwater projections are not available. Because of the relatively thick asphalt layers in this case study, the impacts of groundwater change are not considered.

2.3 *Life cycle assessment*

Material production includes production of asphalt, gravel, and sand materials. Using the cross section of the road, the total amount of materials needed for each structure was estimated. The transportation stage was quantified considering the use of conventional dumping trucks of ten cubic yards. Construction process considered emissions from asphalt paving, rolling, grading, and compaction of unbound materials, and machinery operations. Rehabilitation includes asphalt mill & fill. Gasoline and diesel consumptions were considered in the road use phase. PaLATE is an Excel-based tool which performs LCA based upon user inputs of detailed road design, material type, machinery information. We use default user input values embedded in PaLATE to estimate constructional impacts of the target road section. We also use SimaPro and information collected from the EPA to estimate impacts of use and maintenances phases. Table 3 provides a list of required materials and equipment in this study and their associated costs and impacts. Five vehicle groups were used to classify the traffic, including car, vans, SUV, light truck and articulated truck. IRI values at each year were used to determine the fuel consumption for each class of vehicle at a certain year.

Table 3 Impact Inputs (1 ton = 907 kg, 1 mile = 1.6 km,1 yd^3 = 0.84 m^2, 1 gal = 3.8 L, and 1 lb = 0.46 kg)

Impact Input	Units	Value	Source
Production			
Asphalt Concrete	MJ/ton	641	SimaPro
Asphalt Concrete	kg CO_2 eq/ton	84.7	SimaPro
Gravel	MJ/ton	265	SimaPro
Gravel	kg CO_2 eq/ton	14.10	SimaPro
Sand	MJ/ton	61.8	SimaPro
Sand	kg CO_2 eq/ton	4.25	SimaPro
Transportation			
Dump Truck Transportation	MJ/ton*mile	5.134	SimaPro
Dump Truck Transportation	kg CO_2 eq/ton*mile	0.321	SimaPro
Construction			
Asphalt Paving (Productivity)	ton/hr	10	PaLATE
Asphalt Rolling – Tandem (Productivity)	ton/hr	395	PaLATE
Unbound Material Compaction (Productivity)	ton/hr	1832	PaLATE
Construction Machine Operation	MJ/hr	10816	SimaPro
Construction Machine Operation	kg CO_2 eq/hr	72	SimaPro
Maintenance			
Asphalt Milling	MJ/yd^3	6.23	SimaPro
Asphalt Milling	kg CO_2 eq/yd^3	0.409	SimaPro
Operation			
Gasoline	MJ/gal	130	EPA
Gasoline	lb CO_2/gal	19.64	EPA
Diesel	MJ/gal	137	EPA
Diesel	lb CO_2/gal	22.38	EPA

3 RESULTS AND DISCUSSIONS

Using the methodology laid out previously, results for each test scenario in the project scope were assessed and global warming potentials for each alternative within the scenario were compared for both historical climate conditions as well as future climate projections.

3.1 *Scenario 1: Comparison of Different Pavement Structures and Levels of Recycling*

As previously mentioned, this scenario was used to understand the impacts and costs associated with varying the pavement structure types and the pavement material compositions. Four amounts of hot mix asphalt (HMA) were used in the various pavement structures tested. In terms of recycled content, three different material combinations were tested.

The impacts in terms of GWP of the twelve alternatives are shown in Figure 2. All the values are normalized to have a fair comparison between the different alternatives. Normalization is very important since each combination has different life spans at which it reached terminal serviceability level. The structures are separated into three groups, each with four results. In each group, the leftmost bar represents the “Standard” pavement structure, and the thickness of HMA used in the pavement layer increases in each subsequent bar to the right. The leftmost group shows the results analyzed using no recycled content (V), the middle shows the virgin/recycled mix (V/R), and the rightmost shows the HMA with 40% recycled asphalt material (R). Each bar is split into the portion of impacts or costs associated with either the construction (solid fill pattern) or operation (cross-hatched fill pattern) life cycle phase. As it can be seen in the plots, the construction phase GWP between the 12 cases vary only slightly when comparted to the operational phase impacts. The small change is primarily coming from use of different structures (affecting quantities of various material production as well as construction process) and to some extent due to use of 40% RAP in asphalt layers for some cases.

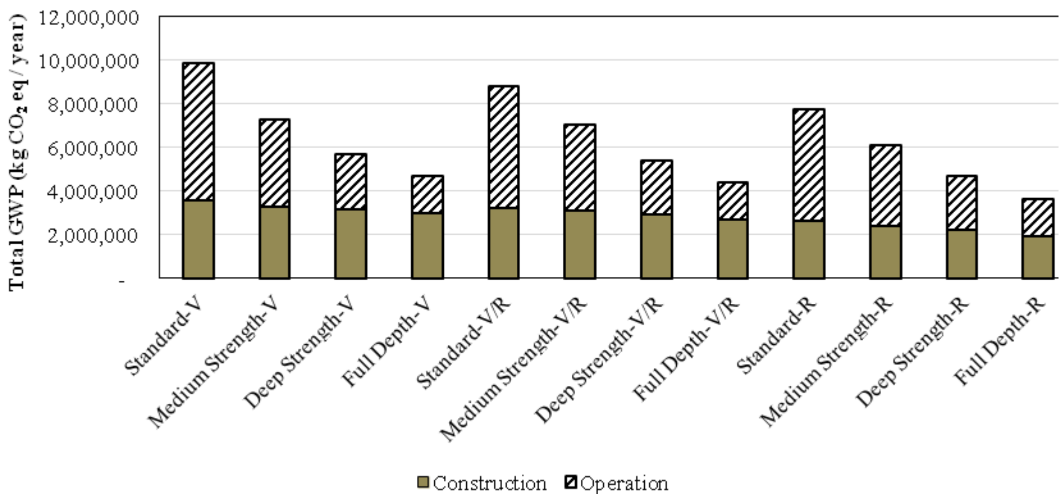

Figure 2 Global Warming Potential (Scenario 1)

Analysis results using future climate projections (cross hatched fill) as opposed to historical climate data (solid fill) are compared in Figure 3. For the first eight structures, less GWP is realized for the alternatives with Virgin materials and Virgin +RAP mixtures when using the historical climate scenario. An opposite trend is noticed for the four remaining structures containing 40% RAP in asphalt mixtures, for these cases the GWP dropped when using future climate projections.

These findings indicate the importance of using appropriate climate information when conducting a comprehensive pavement LCA. As seen in this case study, use of future climate projections (range of 5 to 18 °C of daily average air temperatures) alter the ranking of pavement structure and mix combinations as compared with use of historical climate data (range of 2 to 15 °C of daily average air temperatures), which is the current status quo for pavement analysis. For standard pavement cross-section, when using historical climate data, the use of asphalt mixtures with 40% in all lifts (indicated as Standard-R) shows a higher GWP than alternative of using 40% RAP in only lower asphalt lifts (indicated as Standard-V/R). However when using future climate projections, the GWP of these two alternatives reverse. The counter intuitive trends of the plot can be explained by the physical characteristic difference that were observed between different alternatives. With future climate projections, there was lower roughness in roadways with RAP in mixture as the climate trend is in warming direction. Thus, the total GWP from lower vehicle emissions (due to lower IRI) lead to lowering of GWP in case of using RAP mixes in all asphalt layers.

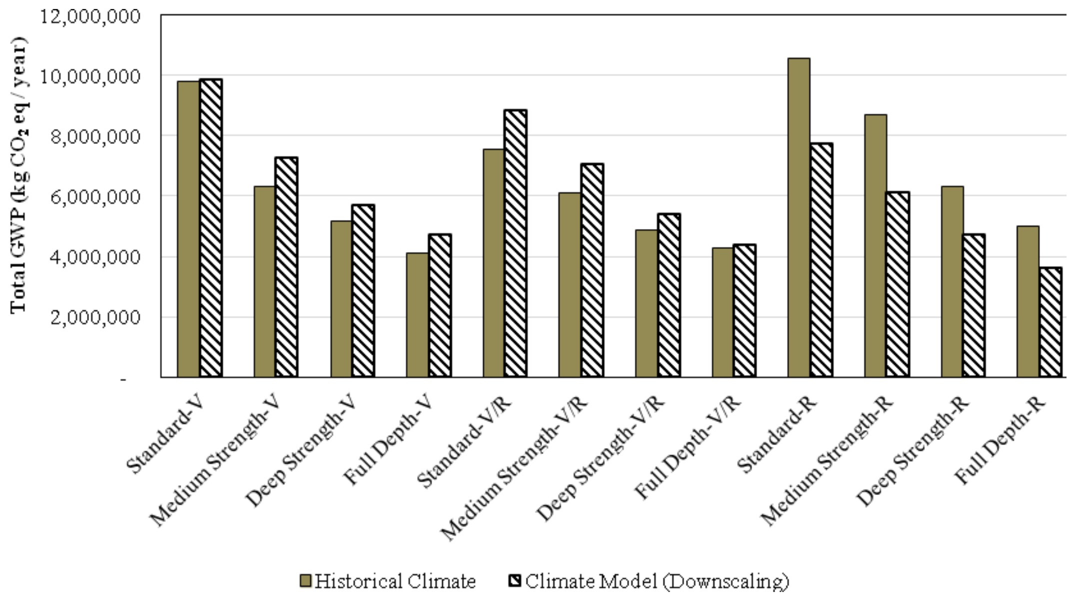

Figure 3 GWP Comparison for Different Pavement Structure and Asphalt Mix Recycling Alternatives with Use of Historical Climate Data and Future Climate Projections.

Information in Figure 4 gives the costs associated with each test scenario that was analyzed. The construction cost is considered in terms of activities related with the transportation agency working on the roadway, while the operation costs are directly connected to drivers of the roadway in terms of fuel consumption. The comparative construction and operational costs of all alternatives for both scenarios (historic climate and future climate projections) are shown in Figure 5. The first 7 cases (structures with Virgin materials and V+R) show lower accumulated cost for the scenario using historical climate data. The Full Depth V+R structure is the only one of this group that has a slightly higher value on the scenario of historical climate data. When comparing the structures with RAP in the four cases, it presents a considerable lower cost in the scenario of climate change. This is associated with better performance of such pavement options in terms of IRI.

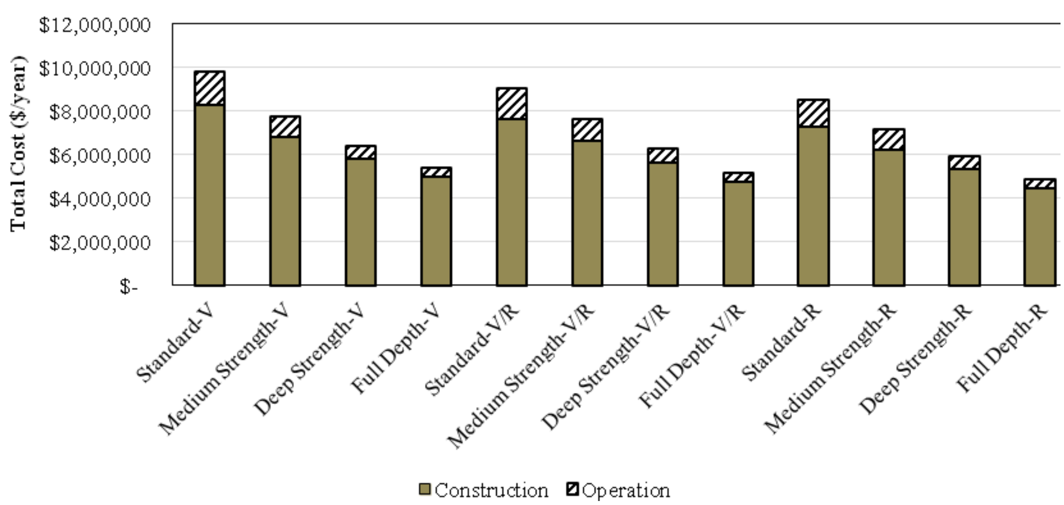

Figure 4 Construction and Operational Costs for Scenario-1 Alternatives using Historic Climate Data

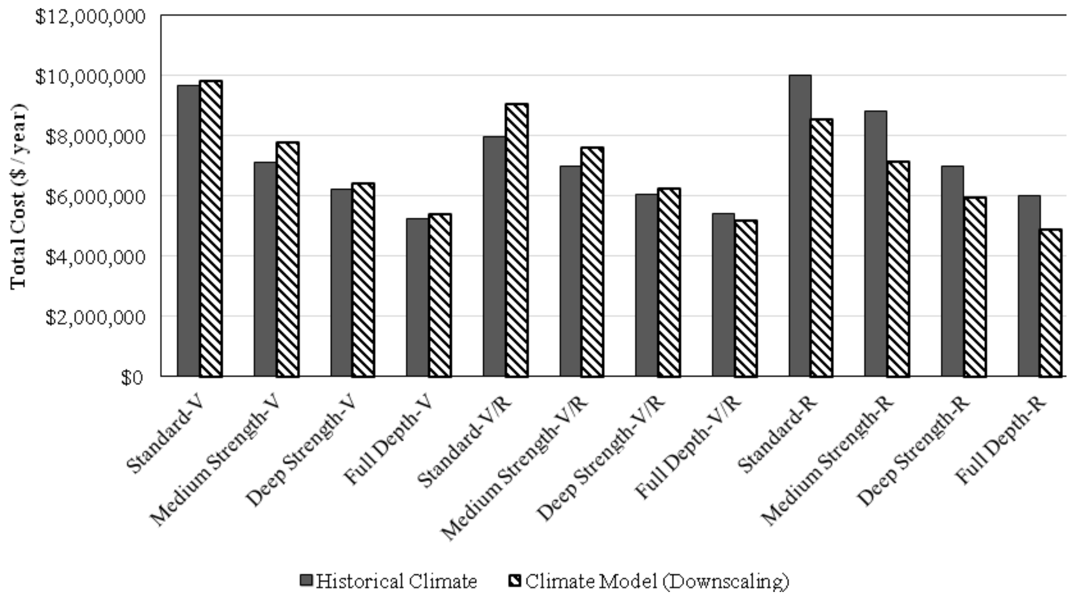

Figure 5 Construction and Operational Cost Comparisons for Scenario-1 Using Historic and Future Climate Projections

3.2 *Scenario 2: Pavement Roughness Threshold for Overlay Rehabilitation*

As discussed in the introductory section of this paper, the second scenario assessed in this work is to make comparisons between different rehabilitation roughness thresholds at which overlay rehabilitation is triggered. Five distinct alternatives were assessed in terms of the IRI at which pavement rehabilitation is undertaken through replacement of top 3 inches of asphalt surface via milling and overlay. Each of these alternatives were simulated for three full rehabilitation cycles. Furthermore, the simulation continued after the third rehabilitation cycle until the terminal IRI of 200 inch/mile (3.2 m/km) is reached. This was necessary to ensure that each alternative was fairly assessed and there was no bias in results due to shorter analysis periods.

For each of the alternatives, annual GWP was calculated and plotted in Figure 6 using the historical climate data. As with previous scenario, the GWP is presented in terms of initial construction (solid fill pattern) and operation (cross-hatched fill pattern). The impact of rehabilitation activity is also shown on the plot (dotted fill pattern). It has to be noted that there is an optimal point in term of GWP at around IRI of 140 inch/mile (2.2 m/km). At this point, there seems to be a balance between the operational emissions from rough pavements and the emissions associated with construction and rehabilitation processes.

A primary focus of this research is to use consequential LCA approach in conjunction with the future climate projections to build additional reliability in LCA results and to demonstrate further need for inclusion of climate change data in current LCA applications to pavement engineering. Total GWP in terms of annual CO_2 equivalent for the five rehabilitation IRI trigger levels using historic climate data (solid fill pattern) and future climate projections (cross-hatched fill pattern) are presented in Figure 7. These GWP values include emissions from initial construction, operation and rehabilitation activities. The results once again demonstrate that the use of future climate projections substantially change the assessment of alternatives. For example, the difference in GWP for using 140 inch/mile (2.2 m/km) versus 160 inch/mile (2.5 m/km) as trigger IRI for mill and overlay is much smaller (4%) when using future climate projections than the one from use of historic climatic data (16%). Since present analysis did not account for factor such as construction related congestion and delays, the use of IRI of 160 inch/mile (2.5 m/km) might be adopted by highway agency as sacrifice of 4% GWP increase when using future climate projections. In fact, the choice of the maintenance trigger is also dependent on the local traffic volume, which can influence congestion and delays (Wang, et al. 2014). However, these influences are out of the scope of this study.

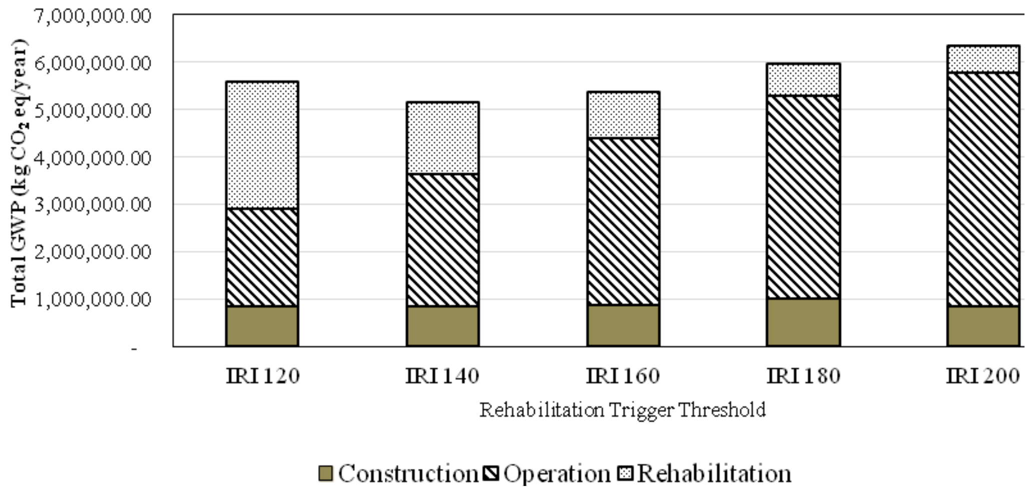

Figure 6 Global Warming Potential for Different Pavement Roughness Thresholds to Trigger Mill and Overlay Rehabilitation

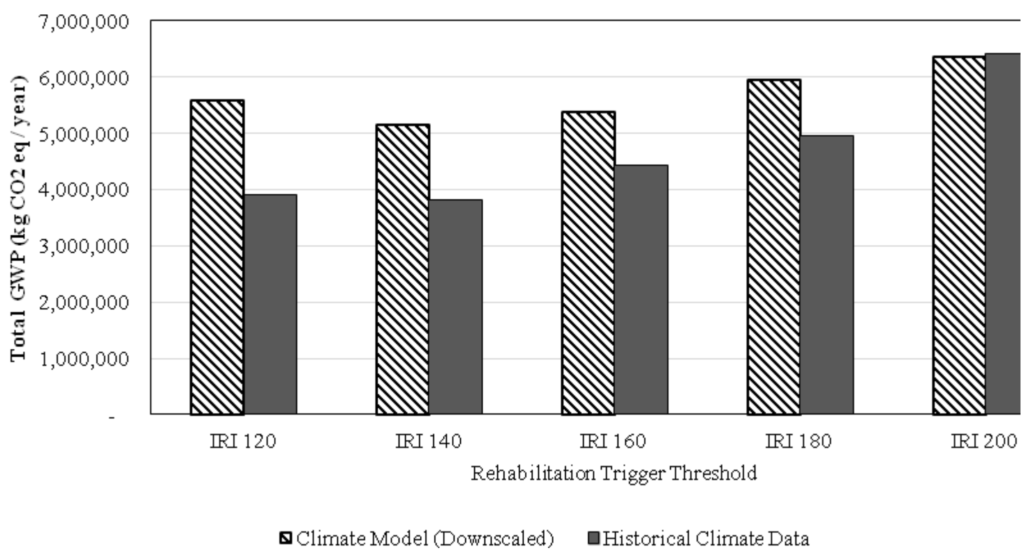

Figure 7 Comparisons of Global Warming Potential for Different Mill and Overlay Pavement Roughness Thresholds for Analysis Conducted using Historical Climate and Future Climate Projections (100 in/mi = 1.58 m/km)

As with previous scenario, the total equivalent annual cost (initial construction, vehicle operation in terms of fuel consumption and rehabilitation costs) were also determined for each alternative. The breakdown and total cost for each alternative is shown in Figure 8. As with GWP, the costs also show an optimality condition for the 180 inch/mile IRI threshold for mill and overlay activity.

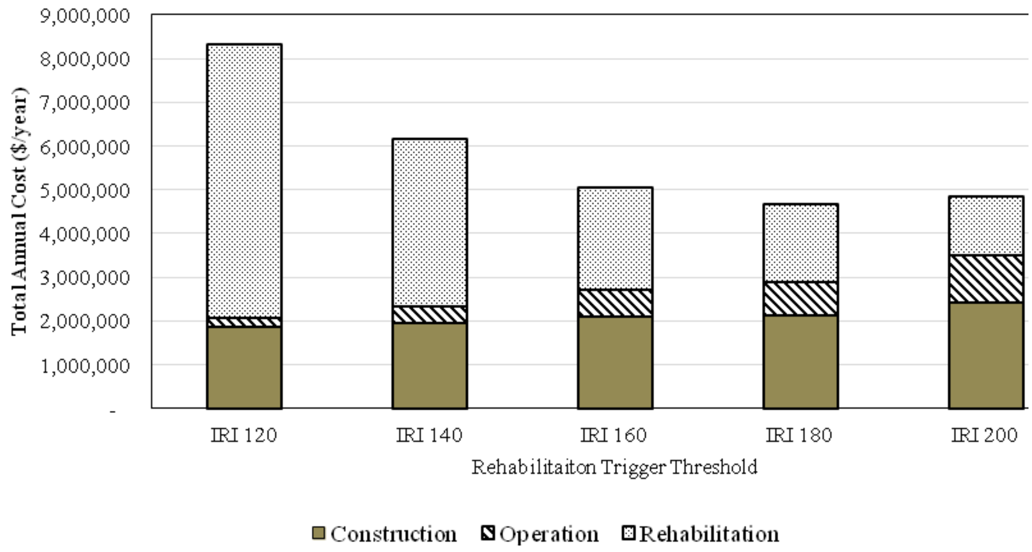

Figure 8 Total Costs for Different Mill and Overlay Pavement Roughness Thresholds

Finally, total cost comparisons between analyses using historic climatic data (solid fill pattern) and future climatic projections (cross-hatched fill pattern) are presented in Figure 9. Life cycle costs from use of downscaled climatic data from future projections again show substantially different results as compared to use of historic climate data.

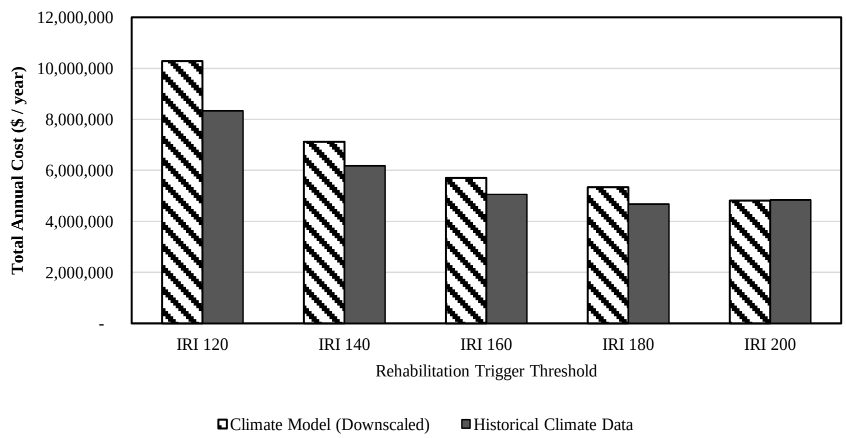

Figure 9 Comparison of Total Annual Costs for Different Mill and Overlay Pavement Roughness Thresholds for Analysis Conducted using Historic Climate Data and Future Climate Projections

4 SUMMARY, CONCLUSIONS AND FUTURE RESEARCH

This paper presents results of a consequential LCA conducted on a segment of interstate highway in the northeastern United States. The uniqueness of this research is to combine future climatic data in pavement performance evaluation to increase robustness of the LCA findings. Downscaled climatic projections from CMIP5 were utilized in this research. Two scenarios were assessed for making comparative analysis: evaluation of different pavement structure and asphalt mixture recycling amounts, and use of different pavement roughness trigger values for mill and overlay decision process. As with other research, it was found that the operational phase of roadways has a substantial impact on the GWP and life cycle costs, however it was clearly seen in results that the optimal alternative from LCA change substantially when using downscaled future climate projections as opposed to historic climate data. Major conclusions form this research can be summarized as following:

- LCA can provide a good decision process to compare different design and planning alternatives, such as, selection of different materials and structures or rehabilitation decision processes. Use of pavement performance model is critical in such process to ensure that reliable operational phase quantification is made.
- Results presented herein clearly showed that LCA findings change drastically with use of future climate information as opposed to historic climate data.
- Framework presented in this paper provides demonstration of using climate change aware LCA that can be easily implemented by public highway agencies to provide design and operational guidance for roadways.

A number of areas for future research were also identified during the present research effort. Major necessary efforts include:

- Present work utilized Pavement ME as primary tool for pavement performance curve development. While PavementME is quite comprehensive, it requires a detailed calibration process to make it reliable for a local region. An alternative would be to use pavement performance curves from pavement or asset management systems that are relevant to a specific region for the materials in that region.
- With changing climate, it is necessary to use reliable future climate projections in LCA process. In reality, the emissions and GWP from analysis like the ones presented in this paper have a certain and quantifiable effect on future climate. Thus, this work can be extended to also take the future climate impact of the comparison alternatives into consideration.
- Effect of climate change on the equipment and vehicle efficiencies need to be accounted to improve reliability of the GWP calculations.

5 ACKNOWLEDGEMENTS

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