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Life Cycle Assessment Based Framework for Design and Maintenance of Roadways in the Cities of Tomorrow

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Introduction

In order to nurture development of the cities of tomorrow, the urban transportation infrastructure needs to be safe, sustainable and resilient. To achieve resilient, safe, and sustainable roadways, the design, management and operation of pavement infrastructure requires: (1) smart sensing for infrastructure health monitoring as well as to ensure safe operational conditions; (2) an adaptation framework to make infrastructure resilient to the climate change; and (3) a life cycle assessment-based decision system to ensure economic, environmental and social sustainability in the design and management practices. The main objective of this paper is to present a climate-change informed life-cycle assessment (LCA) framework to aid in design, maintenance, and operational decisions of urban and suburban roadways with the goal of decarbonization. This framework is expected to be part of a larger resilient, sustainable, and adaptable roadway design, management, and operation system for the cities of tomorrow called SMARTPAVE.

The current engineering processes for pavement design, management and operations of roadways have tremendous economic, environmental, and social impacts (Haslett et al., 2019; Novak et al., 2020). This is especially true in urban areas due to high traffic volumes, needs of local businesses, and most importantly due to provision of roadways as a necessary link in daily lives for urban citizens (work commutes, travel to school, emergency response, etc.). Significant vulnerabilities of roadway infrastructure to changing climate has been well documented (Jacobs et al., 2018, Stoner et al., 2019). Unfortunately, current engineering processes have not been developed to readily adapt to changing climate nor do they utilize holistic assessment to balance economic and environmental (global warming) impacts. Life Cycle Assessment (LCA) can provide necessary methodology to lower global warming potential of road transportation activities, however, LCA needs to incorporate the future climate conditions to yield reliable decision support to engineers. Similarly, many LCA methodologies in pavement engineering selectively choose system boundaries that do not incorporate the use phase of road infrastructure (so called “cradle to gate” system boundary). Use phase is critical to ensure decarbonization goals, since use phase contributes to significantly larger carbon footprint as compared to all other phases. By incorporating use phase in LCA, decision makers can also assess various traffic management strategies as well vehicular innovations and their corresponding impacts on decarbonization efforts.

A brief overview of a climate-change informed pavement LCA methodology that incorporates roadway use phase and utilizes mechanistically assessed pavement performance inputs is presented next.

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Methodology

The pavement LCA framework presented herein was developed on the previous research by Haslett et al. (2019). This pavement LCA system incorporates the realistic traffic conditions for assessing global warming potential (GWP) of an urban roadway during all phases (construction, maintenance, and use). Key attributes and features of the LCA system are listed and briefly described below:

- (1) **Materials and Construction Inventory:** Primary LCA inventory with unit costs and impacts (GWP and cumulative energy demands) has been developed to cover most common pavement construction materials, construction procedures (initial construction, maintenance, and reconstruction) and material transport processes. For heterogeneous composites, such as bituminous mixtures, inventory requires provision of specific composition (by weight or volume) to account for material-to-material differences and to account for usage of recycled asphalt materials.
- (2) **System Boundary:** Current approach utilizes a specific geometric boundary of roadway that is being evaluated. A time boundary also needs to be established for the analysis duration. Since end of life is unfeasible for roadways as it is for many other commodity items, the current system utilizes an approach where analysis time is chosen to represent a minimum of three full pavement reconstruction cycles to ensure that analysis is sufficiently long to keep LCA results relevant and fair between compared alternatives. Remaining serviceable lives and corresponding impacts at end of analysis time are discounted back as a credit.
- (3) **Vehicular Emissions:** To incorporate effects of performance differences between varying roadway materials, structural design and maintenance strategies, effects of roadway condition on vehicular emissions need to be incorporated. In the proposed LCA system, a United State Environmental Protection Agency's Motor Vehicles Emissions Simulator system was utilized to develop emissions profiles of specific vehicular types with respect to specific road conditions. Road condition here is described in terms of its roughness.
- (4) **Traffic Inputs:** Use phase is a major contributor to roadway's carbon footprint, accurate traffic input in terms of vehicle type distribution is necessary. Further, the proposed system considers various vehicular traffic operational attributes, such as, steady speed, acceleration, deceleration, and idling, thus traffic inputs should also include flow characteristics (specifically times and extents of congestions). In the LCA system discussed herein, a Google® maps based realistic traffic data input is utilized. Google® maps tracks traffic flow characteristics through crowdsourced data and this information is converted to hourly traffic flow patterns that are unique for each hour of each day of week. This information coupled with driving behaviour studies, such as US Strategic Highway Research Program 2 naturalistic driving study, allows to develop specific driving trends for each vehicle class (steady state, acceleration, deceleration and idling phases).
- (5) **Future Climate Projections:** Both roadway infrastructure performance as well as vehicular emissions are significantly sensitive to climatic conditions. To be reliable, LCA system needs to utilize future climatic projections as opposed to historic climatic observations. Through World Climate Research Program (WCRP), the Coupled Model Intercomparison Project (CMIP) provides future

climatic projection with availability to downscale high temporal and geographic resolution data. Current work utilized downscaled data with different emissions scenarios and used it in vehicular emissions and pavement performance predictions.

- (6) Pavement Performance Prediction: Ability to mechanistically capture effects of different pavement materials, traffic conditions and climatic conditions is critical within a roadway LCA system that can consider use phase carbon footprint measures. This criticality is due to an important linkage between pavement surface condition and its impacts on vehicular emissions. Pavement structural distresses, specifically cracking, has important impact on the surface characteristics. Use of mechanistic models (AASHTOWare PavementME) have been adopted for the current LCA system, other tools such as ViscoRoute 2.0 are being considered for future applications.

Main results and anticipated ones

Select results using the LCA system discussed in the previous section are presented in this section. These results are generated using a case-study of a 26km long section of a high-traffic freeway (non-toll roadway) located in the North-Eastern part of the United States. This roadway is constructed with total of six lanes and carries more than 12000 trucks per day in each direction. Detailed hourly traffic distributions for the LCA calculations were obtained from the Massachusetts Transportation Data Management System.

The results presented here (table 1) summarizes consequential analysis conducted to compare two pavement structures (referred to as thin and thick pavement) and three pavement maintenance and rehabilitation (M&R) strategies. The results in terms of GWP are provided for analysis conducted using both historic climate data as well as future climate projections. Future climate projections are representative of an average from all global climatic models in the CMIP5 database for next 30 years using a RCP8.5 (emissions scenario resulting in radiative forcing of 8.5 watt/m² by year 2100). These results demonstrate that use of historic climatic inputs in pavement performance predictions and correspondingly in LCA can significantly deviate the carbon footprint of the roadway transportation activities. In the sample results there was limited difference observe in the operational phase as the road serviceability levels were kept constant between the analyses. Thus, the climate impact on operational carbon footprint is indirectly considered in the construction and maintenance activities.

In summary, this research demonstrates that to achieve goals of decarbonization, it is critical that tools such as LCA be adopted within infrastructure design, maintenance, and operation. Further, it is also very important that all analytical efforts consider changing climatic conditions and use future climatic projections in the pavement and material degradation and performance analyses.

Table 1 Global warming potential of a case example roadway for two pavement designs, and three maintenance and rehabilitation scenarios with and without climate change considerations.

Global Warming Potential (Gg CO ₂ eq)								
M&R Scenario	Thick Pavement Section				Thin Pavement Section			
	Impact	Historical	8.5RCP ^f	%Diff ^g	Impact	Historical	8.5RCP	%Diff
DNR ^a	C/M ^d	4.6	5.7	20.0	C/M	12.8	14.5	11.9
	Ops ^e	13.2	13.2	0.0	Ops	13.2	13.2	0.00
	Total	17.8	18.9	6.0	Total	26.0	27.7	6.2
MO ^b	C/M	3.9	4.6	14.3	C/M	7.9	8.1	3.2
	Ops	13.2	13.2	0.0	Ops	13.2	13.2	0.0
	Total	17.1	17.8	3.7	Total	21.1	21.4	1.2
CIR ^c	C/M	2.9	2.9	1.0	C/M	2.6	2.7	2.8
	Ops	13.2	13.2	0.0	Ops	13.2	13.2	0.0
	Total	16.1	16.1	0.2	Total	15.8	15.9	0.5

^a DNR = Do nothing and reconstruct

^b MO = Mill and overlay

^c CIR = Cold-in-place recycling

^d C/M = Construction and maintenance (agency impact)

^e Ops = Operations (user impact)

^g RCP = Representative concentration pathway

^f %Diff = Percent difference with respect to impacts using historical climate data

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Keywords

Roadways; Life Cycle Assessment; Climate Change; Pavements; Transportation.