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基于寿命周期经济和环境影响的沥青路面罩面策略分析 (Asphalt Pavement Overlay Policy Considering Life-Cycle Economic and Environmental Costs)

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CTECH
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ENVIRONMENT AND COMMUNITY HEALTH

Outline

- Introduction and Objective
- Development of Pavement Roughness Models
- Life Cycle Environmental and Economic Impacts of Various Overlay Strategies
- Summary
- Acknowledgment

Introduction

- Pavement is a critical component of transportation infrastructure
  - support more than 9 trillion tonne-kilometers of freight and more than 15 trillion kilometers passenger trip around the world every year
  - Deteriorate over time with traffic
- Asphalt overlay is the most prevalent maintenance and rehabilitation (M&R) strategy
  - Selection and timing traditionally based on LCCA
  - Environmental impact not considered

Objective

- Incorporate both economic and environmental cost considerations in pavement (asphalt) overlay strategy selection
  - Quantify the effect of asphalt overlay design on long-term pavement roughness progression
  - Evaluate the life-cycle environmental and economic impacts of different overlay strategies
  - Optimize pavement overlay policy for environmental and economic sustainability

Pavement Roughness Models

Pavement Roughness Models

- Pavement roughness, in terms of International Roughness Index (IRI), is used as a primary indicator of pavement performance for M&R decisions
- In the literature: primarily a function of pavement age, limited in the scope of data and variables considered
  - Raymond et al. (2003) developed simple linear regression models between as-built IRI and IRI before overlay
  - Irfan (2010) developed different IRI models for thin hot mix asphalt (HMA) overlay, functional HMA overlay, and structural HMA overlay separately with 5-year data in Indiana. Overlay design and existing structure factors not considered.
  - Khattak et al. (2014) developed a post-overlay IRI progression model with data from 170 asphalt overlay projects in Louisiana. Existing structure factors and distresses not considered.

Pavement Roughness Models

- Two models developed in this study
  - IRI drop model due to overlay
    - random parameters linear regression model
  - Post-overlay IRI progression model
    - random effects linear regression model corrected with first-order autocorrelation
- Pavement data source
  - Federal Highway Administration (FHWA) long-term pavement performance (LTPP) database
  - SPS-3 (Preventive Maintenance), SPS-5 (Rehabilitation), and GPS-6 (AC Overlay)

Distribution of LTPP asphalt overlay projects

IRI Drop Model due to Overlay

- Multiple linear regression

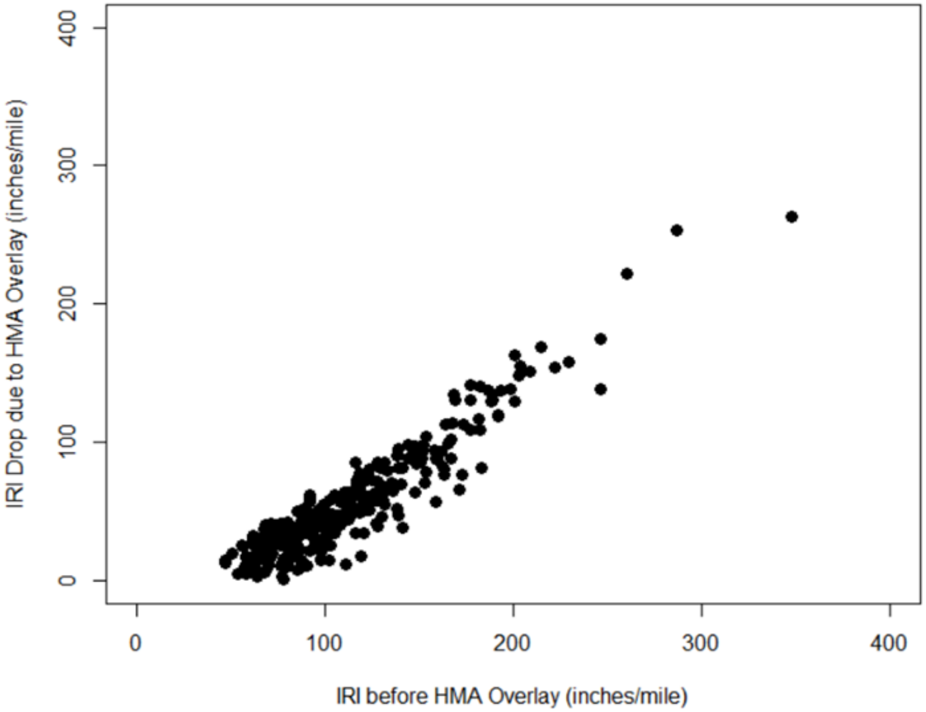
$$IRI_i^d = \beta_0 + \beta_1 X_{i1} + \ldots + \beta_p X_{ip} + \varepsilon_i$$

where, IRI_i^d is IRI drop of overlay project i

- To address the unobserved heterogeneity issue, some parameters (j) are allowed to vary across pavement sections (i)

$$\beta_{ij} = \beta_j + \varphi_{ij}$$

where, φ_{ij} is a randomly distributed term with mean 0 and variance σ_j^2

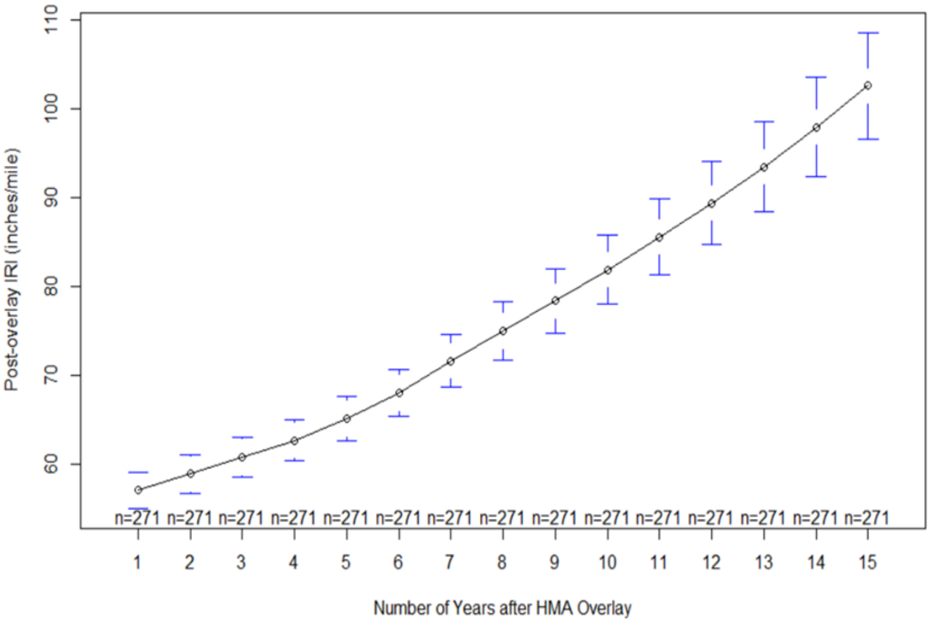


IRI Drop Model due to Overlay

Variable description	Coefficient	t-Statistic
Constant	-40.5963	-15.83
Asphalt overlay thickness (inches)	1.3479	3.22
Pre-overlay IRI (inches/mile)	0.7473	36.86
Asphalt milling indicator × pre-overlay IRI (inches/mile)	0.0708	5.33
Endogenous overlay indicator × pre-overlay IRI (inches/mile)	0.0539	4.19
(standard deviation σ_j for the random coefficient)	(0.0613)	(6.08)
North central region indicator × pre-overlay IRI (inches/mile)	0.0745	3.91
Pre-overlay pavement relative fatigue cracking area (%)	0.1987	3.19
Pre-overlay severe pavement rutting indicator	-3.912	-2.57
Number of observations	270	
R-squared	0.9070	
Adjusted R-squared	0.9045	

Post-overlay IRI Progression Model

- Random effect linear regression model
  - Lagrange Multiplier (LM) test showed it is better than the pooled OLS model
- The first-order time-series correlation of the error term was detected (correlation coefficient of 0.66) and corrected
- Estimated with feasible generalized least squares (FGLS) method



Post-overlay IRI Progression Model

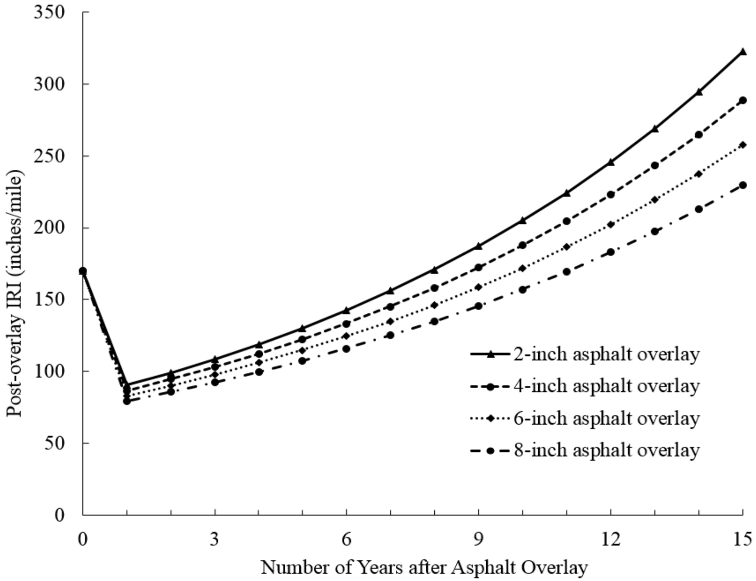
- After estimation, the average value of IRI after t overlay years can be expressed as

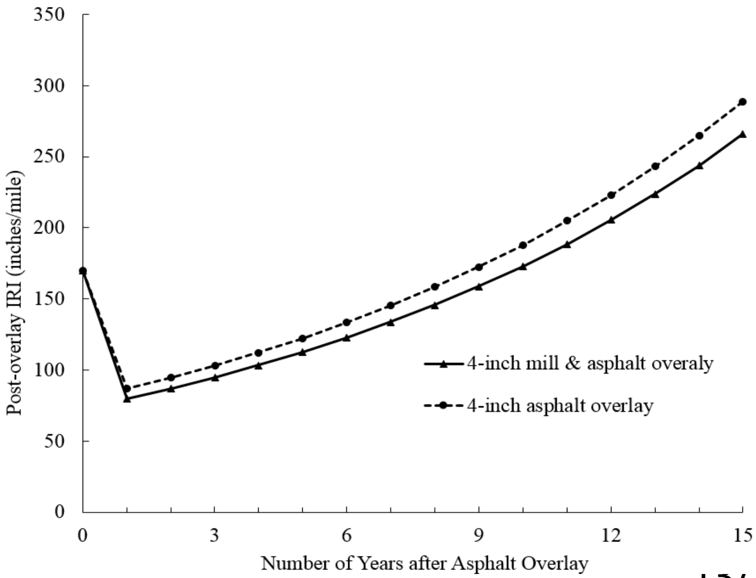
$$\widehat{IRI_{it}} = \widehat{IRI_{i0}} \times exp\left[\begin{pmatrix} -0.0025Thk + 0.0594Df - 0.0023Sn - 0.0161Bd \\ +0.0034Fn - 0.0030Dn + 0.0056Ft + 0.0103Es \\ +0.0062Wf + 0.0731Mt + 0.0105Fz \end{pmatrix} \times t\right]$$

where *Thk* is overlay thickness (inches), *Df* is the average deflection (mm), *Sn* is a high structural number indicator, *Bd* is bound base indicator, *Fn* is fine-grained subgrade indicator, *Dn* is subsurface drainage indicator, *Ft* is extensive-fatigue-cracking indicator, *Es* is annual average daily ESAL (10^6), *Wf* is wet freeze climate zone indicator, *Mt* is average daily maximum temperature in July (100°C), *Fz* is annual average freezing index (1000°C·days). Adjusted R^2 of model estimation is 0.58.

Discussion of IRI Model Results

- Asphalt overlay design factors
  - Overlay thickness
  - -- Milling





- Existing pavement performance
  - has significant effect on overlaid pavement roughness drop and progression
  - IRI drop
    - Factors with positive impact: IRI before overlay, severe fatigue
    - Factor with negative impact: severe rutting
  - IRI progression
    - Severe fatigue cracking before overlay leads to quicker progression
    - IRI before overlay and severe rutting have no significant impact

- Existing pavement structure
  - has significant effect on overlaid pavement roughness progression rate
  - Structures with lower roughness progression rate
    - Asphalt or cement treated subbase
    - Subsurface drainage design
    - Coarse-grained subgrade soil

- Traffic and environmental characteristics
  - has significant effect on overlaid pavement roughness progression rate
  - Significant factors that promote roughness progression rate
    - AADTT
    - Wet-freeze climate zone
    - Annual average freeze index
    - Average daily maximum temperature in July

Life Cycle Environmental and Economic Impacts of Different Pavement Overlay Strategies

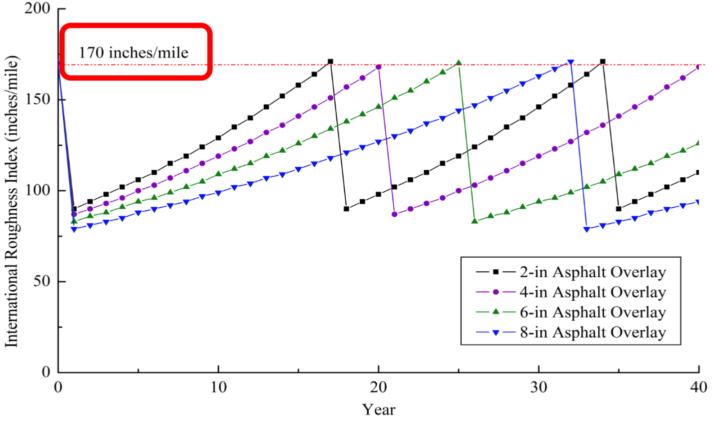
Case Study Goal and Scope

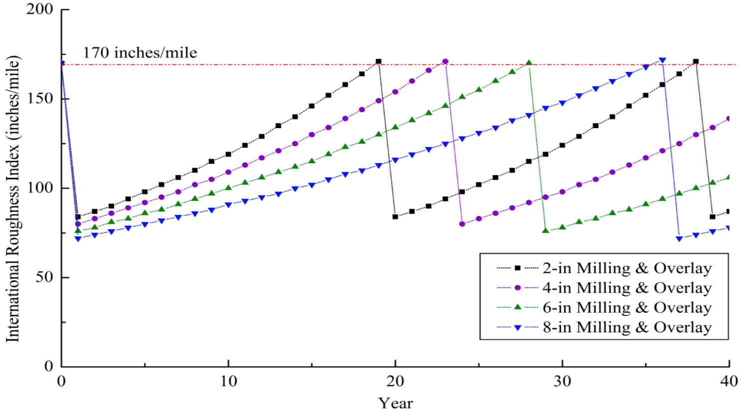
- Goal: evaluate the environmental and economic impacts of different overlay strategies over a 40-year analysis period
  - 16 overlay strategies (4 thicknesses [2,4,6,8 inches]*2 milling [yes or no]* with 30% RAP [yes or no])
- Functional unit
  - A 10-km long, 3.7-m wide overlay system over the outer lane of an existing asphalt pavement in Florida environment

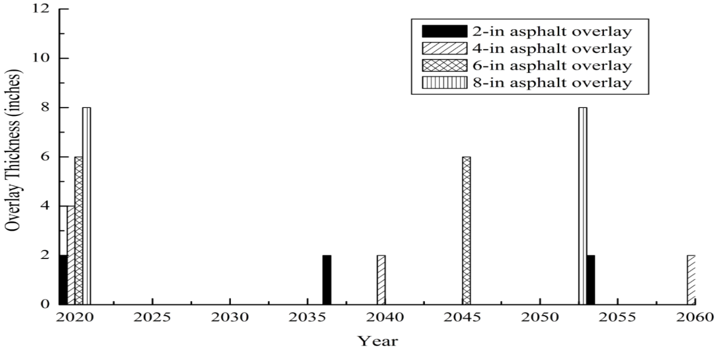
System definition for overlay projects

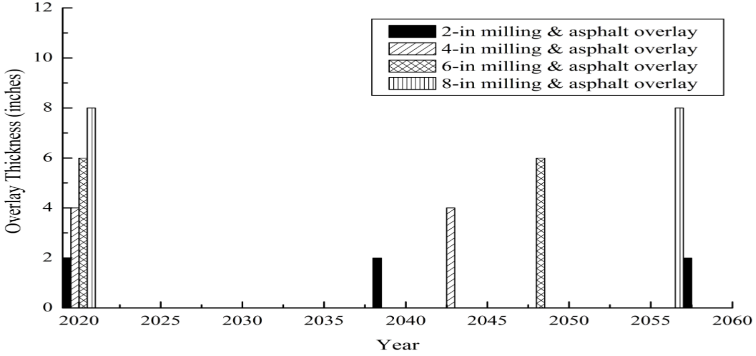
Category	Item Description	Value
General information	Interstate highways (1-yes, 0-no)	1
	Number of lanes in each traffic direction	2
	Speed limit (km/h)	120
	Segment length (km)	10
	Main lane width (m)	3.7
	Inside shoulder width (m)	1.5
	Outside shoulder width (m)	2.5
Existing pavement structure	Structural course SP-12.5 thickness (inches)	4
	Structural course SP-19.0 thickness (inches)	6
	Lime-rock (LR) base course thickness (inches)	10
	Subgrade type (1-coarse-grained subgrade, 0-fine-grined subgrade)	0
	Subsurface drainage condition (1-good, 0-poor)	1
Existing pavement performance	International roughness index (IRI)	170
	Area of fatigue cracking in 10-km lane (%)	4
	Average rut depth in 10-km lane (mm)	8
Traffic information	Annual average daily traffic (AADT) (vehicles/day)	1700, **17,000** 87,000
	Percentage of trucks in AADT (%)	12
	Average truck factor: an equivalent number of 80-kN single axle load	1.3
	Annual traffic growth rate (%)	0
Climatic factors	Climate zone (1-wet freeze zone, 0-otherwise)	0
	Annual average rainfall (mm)	1300
	Annual average freeze index (°C*days)	0
	Annual average daily temperature (°C)	24
	Average daily maximum temperature in July (°C)	34
	Average daily minimum temperature in January (°C)	10
Construction project information	Average distance from plant to site (km)	100
	Average distance from site to stockpile (km)	100
	Average distance from equipment depot to site (km)	100

Rehabilitation schedules and IRI trends

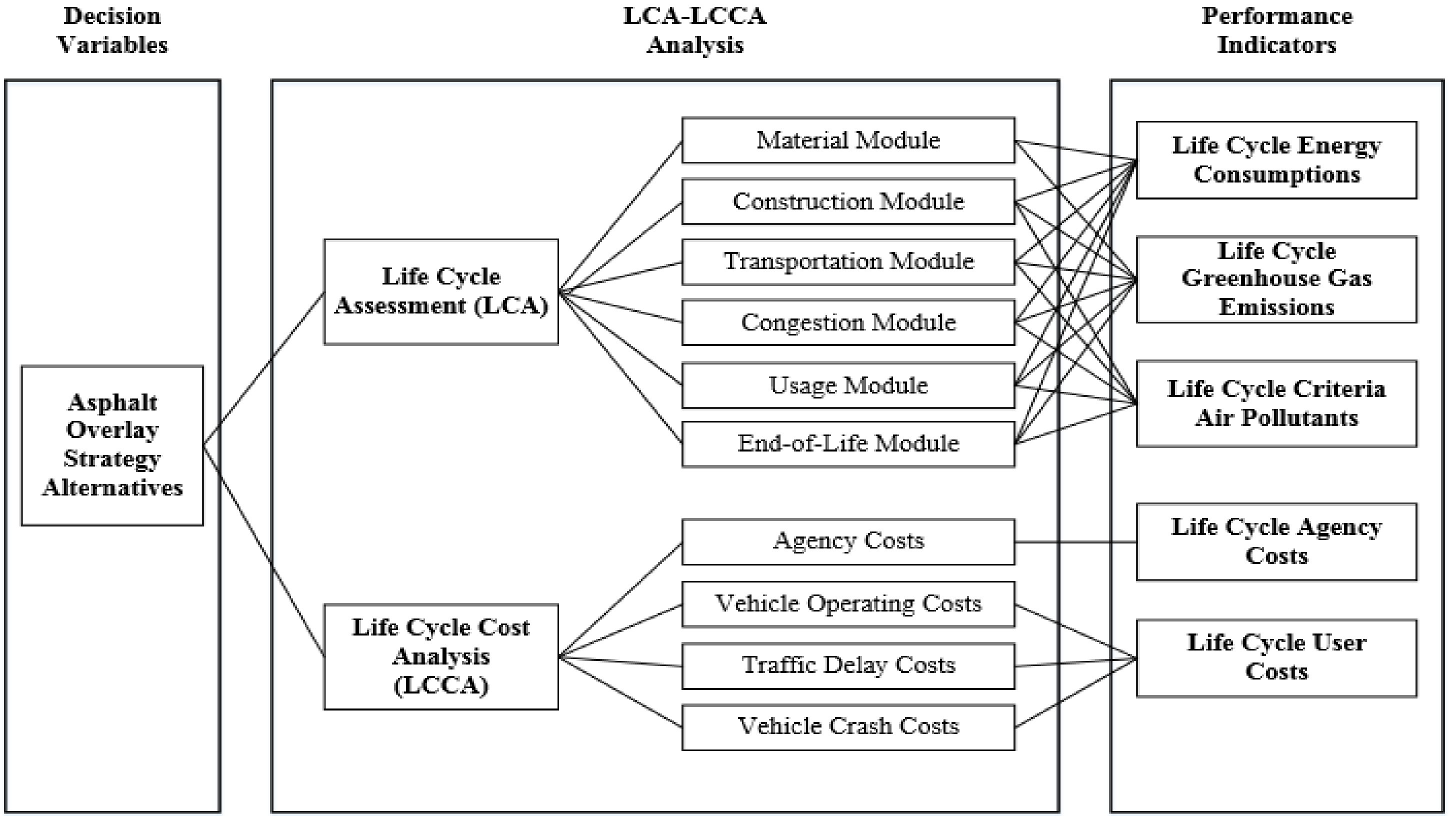








Integrated LCA-LCCA Model



Decision Variables

LCA-LCCA Analysis

Performance Indicators

Asphalt Overlay Strategy Alternatives

Life Cycle Assessment (LCA)

Life Cycle Cost Analysis (LCCA)

Material Module

Construction Module

Transportation Module

Congestion Module

Usage Module

End-of-Life Module

Agency Costs

Vehicle Operating Costs

Traffic Delay Costs

Vehicle Crash Costs

Life Cycle Energy Consumptions

Life Cycle Greenhouse Gas Emissions

Life Cycle Criteria Air Pollutants

Life Cycle Agency Costs

Life Cycle User Costs

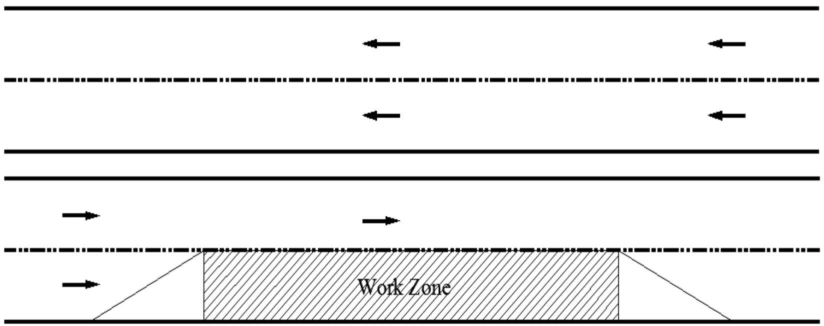
LCA

- Environmental indicator
  - Global warming potential (GWP) (CO_2 equivalent)
  - Acidification potential (AP) (SO_2 equivalent)
  - Human health (HH) particulate (PM2.5 equivalent)
  - Smog potential (SP) (O_3 equivalent)
  - Total primary energy (TPE)

Criteria air pollutants (CAP)

- Computation procedure / Data source
  - Material Module (Manufacturing of SP-12.5, SP-19, RS-1 / Athena Pavement LCA database/FDOT Basis of Estimate Manual)
  - Construction Module (Consumption of fuel [diesel])
  - Transportation Module (100 km distance from plant to cnstrctn sites)

Computation procedure / Data source (cnt'd)



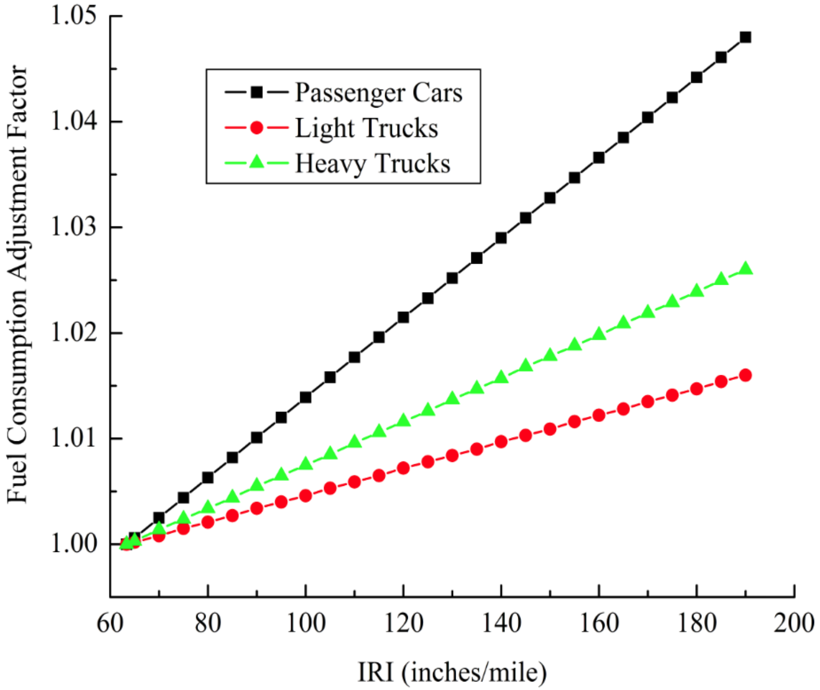
- Congestion Module
  - Lane capacity
    - Normal: 2200 v/h
    - Workzone: 1537 v/h
  - Vehicle (88% car/10% light-duty truck/2%heavy-duty truck)
  - Speed
    - Normal: 120 km/h
    - Workzone: 95 km/h (uncongested), 50 km/h (congested)
  - QuickZone software used to calculate delay, detour rate, and queue length
  - Fuel consumption and vehicle emissions models from the literature were used to quantify environmental impacts

$$Y_{total} = VMT_{queue} Y_{queue} + VMT_{workzone} Y_{workzone} + VMT_{\det our} Y_{\det our} - VMT_{normal} Y_{normal}$$

where, Y is fuel usage or emission value

Computation procedure / Data source (cnt'd)

- Usage Module
  - Effect of pavement roughness on vehicle fuel consumption (Chatti and Zaabar's calibration of the HDM-4 model)
  - Difference of environmental impacts between driving on an overlaid pavement and on an ideally smooth pavement (IRI=63 inches/mile)



Computation procedure / Data source (cnt'd)

- End-of-Life Module
  - Assuming pavement section remains in place at the end of analysis period
  - "Cut-off" allocation method assigning no environmental impacts

LCCA

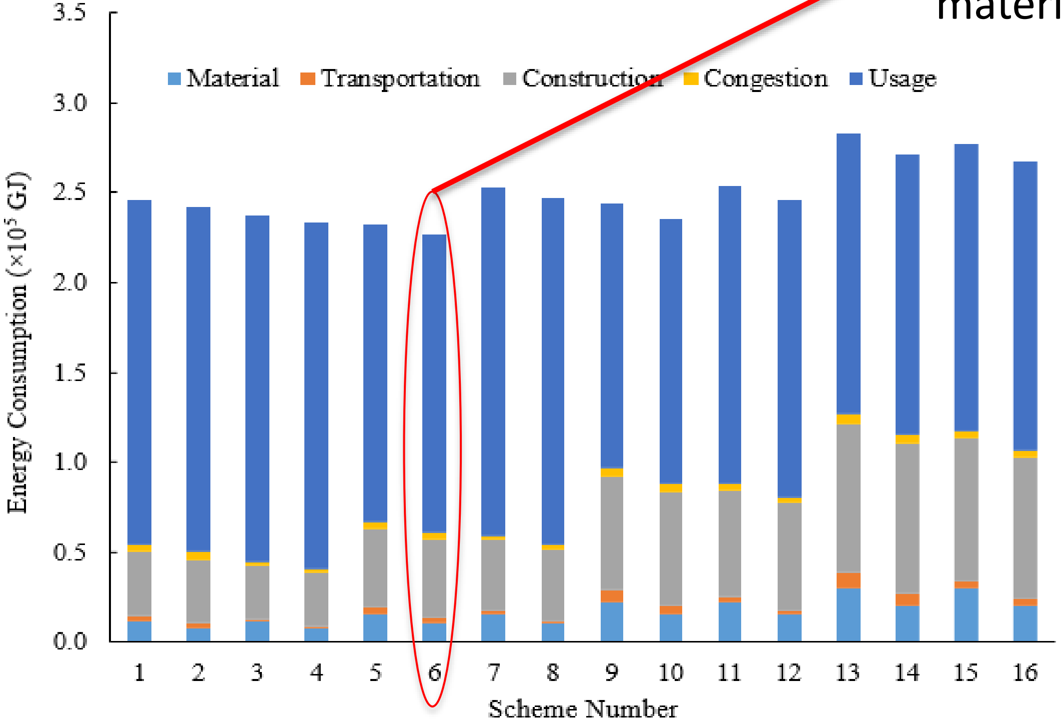
- Analysis period: same as LCA (40 years)
- Discount rate: 3%
- Agency costs
  - material costs, equipment use fee, labor costs (lumped)
  - temporary traffic control ($1000/day)
  - mobilization cost (2% project cost)
- User costs
  - vehicle operating costs (extra fuel consumption relative to smooth pavement)
  - user delay costs (car: $11.58/hr, light truck: $18.54/hr, heavy truck: $22.31/hr)
  - vehicle crash costs (work zone: $0.22/VMT; detour: $0.15/VMT)

Overlay Scheme Designations

Scheme	Overlay Thickness (inches)	Milling Operation (1 [yes] or 0 [no])	30% RAP (1 or 0)
1	2	1	0
2	2	1	1
3	2	0	0
4	2	0	1
5	4	1	0
6	4	1	1
7	4	0	0
8	4	0	1
9	6	1	0
10	6	1	1
11	6	0	0
12	6	0	1
13	8	1	0
14	8	1	1
15	8	0	0
16	8	0	1

LCA Results

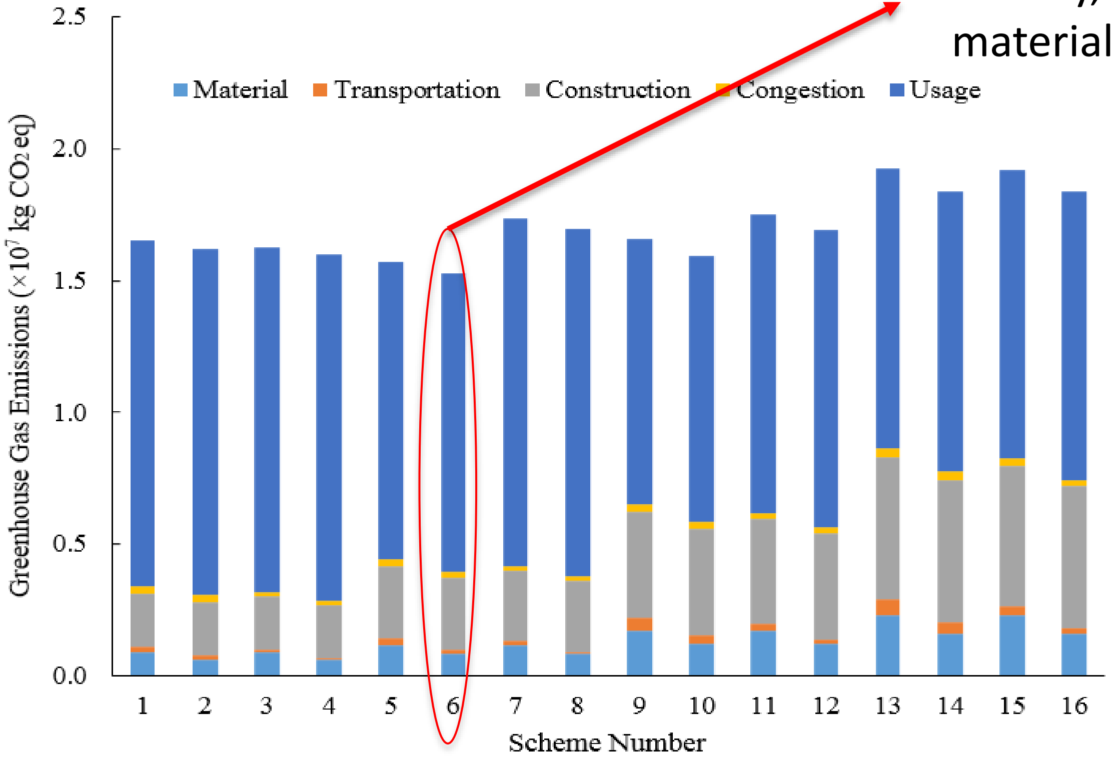
- Total Primary Energy (TPE)



4-in milling and asphalt overlay, and 30% RAP materials

LCA Results

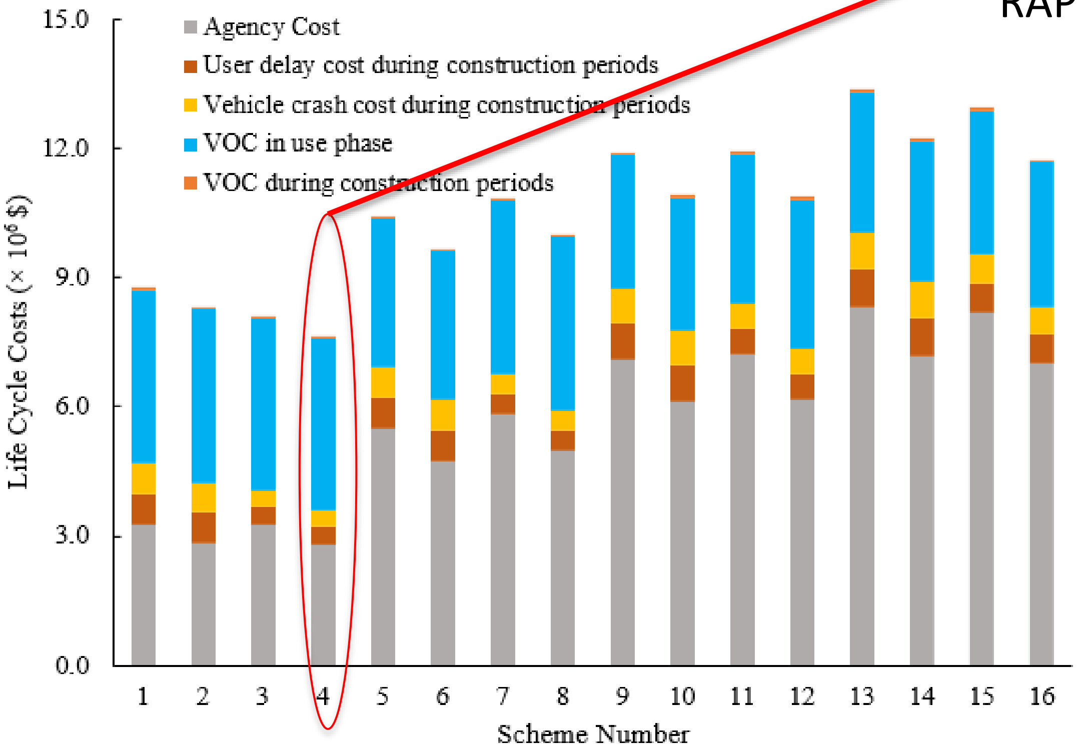
- Global Warming Potential (GWP)



4-in milling and asphalt overlay, and 30% RAP materials

LCCA Results

- Life Cycle Costs



2-in overlay without milling and with 30% RAP materials

Findings of LCA-LCCA of Case Study

- To minimize life cycle energy consumption and GHG emissions, the optimum overlay strategy is 4-in milling and asphalt overlay with 30% RAP.
- To minimize life cycle cost, the optimum overlay strategy is 2-in asphalt overlay with 30% RAP.
- AADT affects results significantly
  - Low traffic volume (e.g., AADT = 1700): material and construction modules dominate in LCA, agency cost dominates in LCCA
  - With increase of traffic volume, usage phase becomes more important in LCA and LCCA
- IRI trigger value also affects LCA and LCCA

Summary and Discussion

- Empirical models of pavement roughness drop and progression due to overlay were developed based on LTTP data.
- Case study of various overlay strategies evaluated by LCA and LCCA.
- To consider both economic and environmental costs in selecting optimal pavement rehabilitation strategies, a multi-objective optimization algorithm may be applied.

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