Pavement Rehabilitation Policy for Reduced Life-Cycle Cost and Environmental Impact Based on Multiple Pavement Performance Measures

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16. Abstract

Highway pavement is a critical component of the highway transportation infrastructure. After the construction of a pavement system, pavement condition will deteriorate over time due to a combination effect of material aging, traffic loading, and environmental factors. As pavement condition deteriorates, vehicle operating costs and their corresponding environmental impacts would increase significantly. To restore the pavement performance and to reduce its adverse effects on public users and environment, asphalt overlay activities are conducted frequently during the service life of a pavement. Meanwhile, asphalt overlay itself consumes large amounts of energy and natural resources. The purpose of this research is to guide highway agencies to optimize flexible pavement overlay strategies using the integrated cycle assessment (LCA) - life cycle cost analysis (LCCA) approach. In the study, a post-overlay pavement roughness progression model in terms of international roughness index (IRI) is firstly developed to evaluate the effect of asphalt overlay design factors on pavement roughness progression. Then, by incorporating the proposed post-overlay IRI model in the integrated LCA-LCCA framework, the life cycle environmental and economic impacts of different overlay strategies are evaluated. Finally, a multi-objective optimization framework is proposed for identifying the eco-friendly and cost-effective asphalt overlay strategy. Based on the comparative analysis results, the inclusion of 30% reclaimed asphalt pavement (RAP) in asphalt overlay is found to reduce life cycle energy consumption, greenhouse gas (GHG) emissions, criteria air pollutants, and life cycle costs. For asphalt overlay projects, pavement surface roughness effects, construction activity, and material production are three major contributors to life cycle energy consumption and GHG emissions. The usage phase vehicle operating costs and agency costs are two dominant factors in the LCCA of different asphalt overlay strategies. Based on a sensitivity analysis, traffic level and IRI trigger value for asphalt overlay have a significant effect on the life cycle environmental and economic sustainability of overlaid pavements.

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***Abstract*— Highway pavement is a critical component of the highway transportation infrastructure. After the construction of a pavement system, pavement condition will deteriorate over time due to a combination effect of material aging, traffic loading, and environmental factors. As pavement condition deteriorates, vehicle operating costs and their corresponding environmental impacts would increase significantly. To restore the pavement performance and to reduce its adverse effects on public users and environment, asphalt overlay activities are conducted frequently during the service life of a pavement. Meanwhile, asphalt overlay itself consumes large amounts of energy and natural resources. The purpose of this research is to guide highway agencies to optimize flexible pavement overlay strategies using the integrated cycle assessment (LCA) - life cycle cost analysis (LCCA) approach. In the study, a post-overlay pavement roughness progression model in terms of international roughness index (IRI) is firstly developed to evaluate the effect of asphalt overlay design factors on pavement roughness progression. Then, by incorporating the proposed post-overlay IRI model in the integrated LCA-LCCA framework, the life cycle environmental and economic impacts of different overlay strategies are evaluated. Finally, a multi-objective optimization framework is proposed for identifying the eco-friendly and cost-effective asphalt overlay strategy. Based on the comparative analysis results, the inclusion of 30% reclaimed asphalt pavement (RAP) in asphalt overlay is found to reduce life cycle energy consumption, greenhouse gas (GHG) emissions, criteria air pollutants, and life cycle costs. For asphalt overlay projects, pavement surface roughness effects, construction activity, and material production are three major contributors to life cycle energy consumption and GHG emissions. The usage phase vehicle operating costs and agency costs are two dominant factors in the LCCA of different asphalt overlay strategies. Based on a sensitivity analysis, traffic level and IRI trigger value for asphalt overlay have a significant effect on the life cycle environmental and economic sustainability of overlaid pavements.**

***Index Terms*—** pavement overlay, life cycle assessment, life cycle cost analysis, international roughness index, sensitivity analysis, multi-objective optimization

I. INTRODUCTION

AN effective highway transportation infrastructure is a key factor in economic and social development [1]. Highway pavements, as a critical component of the highway transportation infrastructure support more than nine trillion tonne-kilometers of freight and transport passengers more than fifteen trillion kilometers around the world every year [2,3]. After the construction of a pavement system, pavement condition will deteriorate over time due to a combination effect of material aging, traffic loading, and environmental factors. As pavement condition deteriorates, vehicle operating costs and their corresponding environmental impacts would increase significantly [4]. When pavement condition deteriorates to a certain level, pavement maintenance and rehabilitation (M&R) activities are typically implemented to restore pavement performance and reduce its adverse effects on public users. Asphalt overlay, as the most prevalent M&R activity, can benefit users by providing a smooth and quiet pavement. Meanwhile, asphalt overlay itself consumes a huge amount of energy and natural resources. Thus, significant environmental improvement and budget saving may be achieved by making eco-friendly and cost-effective decisions in selecting asphalt overlay strategy.

However, in practice, traditional selection and scheduling of asphalt overlay strategies are primarily based on minimization of life cycle costs (LCC) incurred by highway agencies and public users. The environmental impacts of asphalt overlay strategies are not considered.

In recent years, several researchers have compared the environmental impacts of different pavement overlay systems with the life cycle assessment (LCA) approach. In 2009, Zhang et al. estimated the environmental impacts for three pavement overlay systems (i.e., concrete overlay, asphalt overlay, and engineered cementitious composites [ECC] overlay) using a pavement LCA model. They found that, compared to a conventional concrete overlay system, the ECC overlay system can reduce the life-cycle energy consumption and greenhouse gas (GHG) emissions significantly in the case study [5]. In 2012, Yu and Lu compared the environmental impacts of three pavement overlay systems (concrete overlay, asphalt overlay, and crack, seat and asphalt overlay) with the LCA approach. They found that, for the case study, concrete overlay has less environmental burdens than asphalt overlay [6]. However, these two studies only considered the effect of overlay type on environmental impacts. The effects of detailed asphalt overlay design (e.g., overlay thickness, milling or not) on pavement deterioration and its corresponding life cycle environmental impacts were not considered.

The purpose of this research is to guide highway agencies to optimize flexible pavement overlay strategies with the integrated life cycle assessment (LCA) - life cycle cost analysis (LCCA) approach. To achieve the above objective, three questions need to be addressed: (1) how to quantify the effect of asphalt overlay design on long-term pavement roughness progression? (2) how to evaluate the life-cycle environmental and economic impacts of different pavement overlay strategies? (3) how to optimize pavement overlay policy for environmental and economic sustainability?

The remainder of the report is structured as follows. The post-overlay pavement roughness progression model is developed in Chapter II. The comparative analysis for environmental and economic impacts of different pavement overlay strategies is conducted in Chapter III. The multi-objective optimization approach for identifying the eco-friendly and cost-effective pavement overlay strategy is proposed and illustrated in Chapter IV. Finally, the conclusions are summarized in Chapter V.

II. PAVEMENT ROUGHNESS PROGRESSION MODEL

A. *Introduction*

A pavement roughness progression model is defined as the pavement roughness trend over the analysis period of time, which models the relationship between the international roughness index (IRI) and a set of causal factors. To quantify the life-cycle environmental impacts and costs of pavement overlay strategies during the pavement usage phase, a post-overlay pavement roughness progression model is necessary. However, in most current LCA studies, pavement roughness progression models only have pavement age as the predictor. The effects of traffic volume, pavement structure, and environmental characteristics on pavement roughness progression are not considered. In addition, instead of using IRI, some researchers developed pavement deterioration models in terms of regional performance indicators. The transformation from regional performance indicators to IRI would add more uncertainty in the prediction of pavement roughness progression [4].

To develop a comprehensive empirical relationship between asphalt overlay design factors and long-term pavement roughness progression, previous studies on post-overlay flexible pavement roughness models are reviewed as follows. In 2003, Raymond et al. developed a series of simple linear regression models between as-built IRI and IRI prior to asphalt overlay under different combinations of overlay design factors [7]. They found that as-built IRI would increase linearly with IRI prior to asphalt overlay. However, due to the small sample size of each subgroup data and the low goodness-of-fit value of each model, the prediction accuracy of as-built IRI models is an issue. In 2010, Irfan developed different post-overlay pavement IRI progression models for thin hot mix asphalt (HMA) overlay, functional HMA overlay, and structural HMA overlay separately with five-year pavement performance data in Indiana [8]. He found that annual average truck traffic and annual average freezing index have significant effects on post-overlay IRI progression rate. However, the effects of detailed asphalt overlay design and existing pavement structure factors on long-term post-overlay IRI progression were not considered. In 2014, Khattak et al. developed a post-overlay IRI progression model with data from 170 asphalt overlay projects in Louisiana [9]. They found that overlay thickness and overlay age are contributing factors of post-overlay IRI progression. However, the effects of existing pavement structure factors and pavement distresses on post-overlay IRI progression were not considered. In addition, since the proposed models in the above two studies were based on state-level data, they may not be transferable to other states.

In this study, the relationship between asphalt overlay and post-overlay pavement roughness is quantified with two types of models. To be specific, IRI drop model is firstly developed to predict the instantaneous reduction of IRI due to asphalt overlay activity. Second, a post-overlay IRI progression model is developed to predict the trend of IRI progression over a period of time after asphalt overlay.

The remainder of this chapter is structured as follows. The database used for analysis and descriptive statistics of the possible variables are presented in Section B. The model formulations for random parameters linear regression and random effects linear regression model corrected with first-order autocorrelation are illustrated in Section C. The empirical estimation results of the IRI drop model and post-overlay IRI progression model are presented in Section D. In Section E, discussions about the effects of potential causal factors on post-overlay IRI progression and pavement remaining service life are provided. Finally, Section F summarizes the major findings and provides recommendations to improve pavement management.

B. *Data Collection and Descriptive Analysis*

a. *Data Sources and Collection Procedure*

The sample data used in this study were extracted from two major data sources: (1) Federal Highway Administration (FHWA) long-term pavement performance (LTPP) database; and (2) National Oceanic and Atmospheric Administration (NOAA) climate database. The LTPP pavement sections are classified into two groups: general pavement studies (GPS) and specific pavement studies (SPS). The LTPP GPS and SPS programs were designed to ensure that pavement sections represent a wide variety of different pavement structures located in different environments and subjected to different traffic levels [10]. In this study, LTPP SPS-3 program ("Preventive Maintenance Effective of Flexible Pavement"), SPS-5 program ("Rehabilitation of Flexible Pavement"), and GPS-6 program ("Asphalt Concrete Overlay on Flexible Pavement") were identified for selecting asphalt overlay projects. For SPS-3 program, only pavement sections that had experienced with thin asphalt overlay treatment were selected. For SPS-5 program, since the control sections provide no information related to post-overlay roughness, they were not incorporated in the analysis [11]. In addition, pavement sections whose pavement performance measurements before asphalt overlay were not available were excluded in the study. After being extracted from the LTPP database, 15-year post-overlay IRI data were evaluated for completeness and reasonableness. Some missing data were complemented with an interpolation of data measured during the previous and next survey years. In summary, as shown in Fig. 1, 271 asphalt overlay projects (i.e., 32 SPS-3 pavement sections, 146 SPS-5 pavement sections, and 93 GPS-6 pavement sections) implemented on flexible pavements were identified from the LTPP database.

Fig. 1. Spatial distribution of LTPP asphalt overlay projects

b. *Descriptive Analysis*

The descriptive statistics of the key independent variables used in IRI drop model or IRI progression model are summarized in Tab. 1.

Tab. 1. Descriptive statistics of key variables

Variable Description	Mean	Standard Deviation
IRI before asphalt overlay (inches/mile)	113.887	45.802
IRI after asphalt overlay (inches/mile)	56.870	17.046
IRI drop due to asphalt overlay (inches/mile)	57.017	42.362
Endogeneity indicator (1 if it is in the GPS program, 0 otherwise)	0.343	0.475
Extensive-fatigue-cracking indicator (1 if area of fatigue cracking before overlay is over 10% of lane area, 0 otherwise)	0.236	0.425
Severe-rutting indicator (1 if the rut depth before asphalt overlay is over 10 mm, 0 otherwise)	0.395	0.490
Subsurface drainage indicator (1 if subsurface drainage exists, 0 otherwise)	0.103	0.304
Fine-grained subgrade indicator (1 if subgrade material is fine-grained soil, 0 otherwise.)	0.314	0.464
Bound (treated) subbase indicator (1 if subbase type is asphalt or cement treated subbase, 0 otherwise)	0.092	0.289
Subbase layer thickness (inches)	9.956	9.137
Bound (treated) base indicator (1 if base type is asphalt or cement treated base, 0 otherwise)	0.435	0.496
Asphalt overlay thickness (inches)	3.546	1.948
Recycled overlay material (1 if overlay material consists of 30% reclaimed asphalt pavement [RAP] material, 0 otherwise)	0.255	0.436
Milling operation indicator (1 if pavement is milled before asphalt overlay, 0 otherwise)	0.524	0.499
Annual average freezing index (1000°C·days)	0.329	0.462
Wet freeze climate zone indicator (1 if climate zone is wet and freeze zone, 0 otherwise)	0.255	0.436
Average daily maximum temperature in July (100 °C)	0.309	0.052
Average deflection at the center of 9-kip load plate (mm)	0.220	0.109
Higher structure number indicator (1 if structure number is greater than 5, 0 otherwise)	0.568	0.495
Annual average daily 18-kip ESAL (1000 KESAL)	0.798	1.251

Based on Tab. 1, the average as-built pavement roughness over the sample is about 57 inches/mile. The range of IRI drop value due to the asphalt overlay is between 2 and 263 inches/mile. To determine the function form of IRI drop model, the relationship between IRI drop and IRI before HMA overlay is shown in Fig. 2. As can be seen in Fig. 2, the reduction value of IRI due to asphalt overlay seems to increase with the initial IRI before asphalt overlay in an approximately linear way.

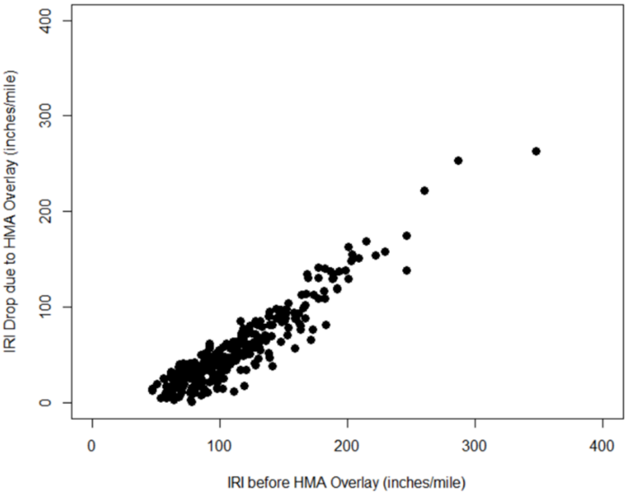

Fig. 2. Relationship between IRI drop and initial IRI

The relationship between post-overlay IRI and number of years after asphalt overlay is shown in Fig. 3. As can be seen in Fig. 3, the average post-overlay roughness increases with the number of overlay years in a non-linear way. In addition, the annual variance of average post-overlay roughness over the sample pavement sections increases with the number of years after asphalt overlay. It indicates that positive time-series correlation issue exists in post-overlay IRI progression data.

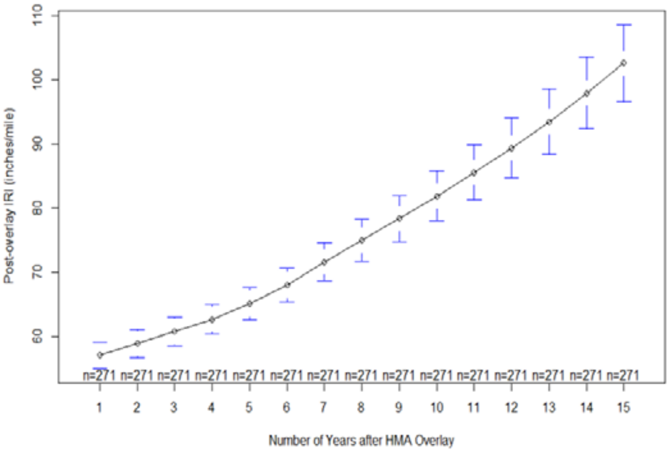

Fig. 3. Post-overlay IRI progression trend

C. *Statistical Methodology*

a. *IRI Drop Model*

Since the relationship between IRI drop and initial IRI before overlay is linear (Fig. 2), a multiple linear regression model is developed in Eq. (1).

$$IRI_i^d = \beta_0 + \beta_1 X_{i1} + \ldots + \beta_p X_{ip} + \varepsilon_i \qquad (1)$$

where IRI_i^d is the IRI drop of overlay project i due to asphalt overlay, $\left(\beta_0, \beta_1, \ldots, \beta_p\right)$ is a vector of estimable parameters, $\left(X_{i1}, X_{i2}, \ldots, X_{ip}\right)$ is a vector of possible independent variables for pavement section i, and $\varepsilon_i \sim N\left(0, \sigma^2\right)$ is a random error term.

To address the unobserved heterogeneity issue in the IRI drop model, a random parameters linear regression model can be developed to allow some parameters to vary across pavement sections, rather than being fixed as they are in traditional linear regression models [12]. The equation of regression coefficients for random parameters model is given in Eq. (2).

$$\beta_{ij} = \beta_j + \varphi_{ij} \tag{2}$$

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

b. IRI Progression Model

Since pavement roughness progression model form is typically exponential ($IRI_t = IRI_0 e^{rt}$) [13], the post-overlay IRI progression model is developed in Eq. (3).

$$IRI_{it}^p = IRI_{i0} e^{\left[\left(\gamma_1 X_{i1} + \gamma_2 X_{i2} + \cdots + \gamma_q X_{iq}\right)t + \mu_{it}\right]} \tag{3}$$

where IRI_{it}^p is the IRI of pavement section i after t overlay years, IRI_{i0} is the as-built IRI of pavement section i, $\left(\gamma_1, \gamma_2, \ldots, \gamma_q\right)$ is a vector of estimable parameters, $\left(X_{i1}, X_{i2}, \ldots, X_{iq}\right)$ is a vector of possible independent variables for pavement section i, t is number of years after asphalt overlay, μ_{it} is a random error term. The above model form can be adjusted in Eq. (4).

$$IRI_{it}^* = \left(\gamma_1 X_{i1} + \gamma_2 X_{i2} + \cdots + \gamma_q X_{iq}\right)t + \mu_{it} \tag{4}$$

where $IRI_{it}^* = \log\left(IRI_{it}^p / IRI_{i0}\right)$.

Since the data set consists of panel data, a random effects model with one-way error component can be used [12]. This type of model can consider both the random effects of individual pavement section (invariant of time) and a random error term over time at each location. The random error term μ_{it} can be presented in Eq. (5).

$$\mu_{it} = \upsilon_i + \tau_{it} \tag{5}$$

where υ_i is a pavement section-specific error term $\upsilon_i \sim N\left(0, \sigma_v^2\right)$. The error term captures the unobserved heterogeneity between different pavement sections. To address the possible time-serial correlation in the same pavement section, the above random effects model can be estimated with an auto-correlated error structure (shown in Eq. (6)).

$$\tau_{i,t} = \rho \tau_{i,t-1} + \eta_{it} \tag{6}$$

where $\eta_{it} \sim N\left(0, \sigma_\eta^2\right)$ is independently and identically distributed.

D. Model Estimation

The software package R version 3.4.3 was used to estimate the IRI drop model and post-overlay IRI progression model with the collected data. In the estimation of fixed parameters linear regression model, outlier test was conducted to identify the possible outliers. Then, after removing one identified outlier, the box-cox transformation was conducted to check whether the transformation of response variable is needed. Based on the estimation, the IRI drop value did not need to be transformed. In the estimation of random parameters linear regression model, several assumptions (normal, lognormal, and uniform distribution) on the random parameters' distribution were evaluated for different variables with a simulated maximum likelihood approach. Finally, five normally distributed random parameters were identified after 200 Halton draws. The estimated random parameters linear regression model for IRI drop is presented in Tab. 2.

Tab. 2. Random parameters linear regression for IRI drop

Variable description	Coefficient	t statistic
Constant	-34.7190	-336.63
standard deviation for the random parameter	(5.5539)	(251.00)
IRI before HMA overlay (inches/mile)	0.6505	646.30
standard deviation for the random parameter	(0.1078)	(505.22)
HMA overlay thickness (inches)	1.8461	131.49
Milling operation indicator	6.9093	129.03
standard deviation for the random parameter	(0.2888)	(9.19)
Interaction term between north central region indicator and IRI before asphalt overlay	0.0847	147.05
standard deviation for the random parameter	(0.0116)	(25.81)
Interaction term between extensive-fatigue-cracking and IRI before HMA overlay	0.0820	154.53
Interaction term between severe-rutting and IRI before HMA overlay	-0.0171	-40.99
Interaction term between endogeneity indicator and IRI before HMA overlay	0.0702	172.66
standard deviation for the random parameter	(0.0414)	(121.47)
Number of observations	270	
Log-likelihood at convergence	-1047.48	

Based on Tab. 2, the as-built IRI can be predicted as the difference between the initial IRI and IRI drop value. The average value of IRI drop ($\hat{IRI}_i^d$) can be calculated with Eq. (7).

$$\begin{aligned}\hat{IRI}_i^d = &-34.72 + 0.65 IRI_c + 1.85 Thk + 6.91 Mill + 0.085(Nc \times IRI_c) \\ &+ 0.082(Fc \times IRI_c) - 0.017(Rt \times IRI_c) + 0.07(En \times IRI_c)\end{aligned} \tag{7}$$

where IRI_c is the critical value for pavement overlay; Thk is overlay thickness (inches), $Mill$ is a milling operation indicator, Nc is a regional indicator, Fc is extensive fatigue cracking indicator, Rt is severe rutting indicator, En is an endogeneity indicator. Then, if the IRI_c is 170 inches/mile, the as-built IRI ($\hat{IRI}_{i0}$) after asphalt overlay can be calculated with Eq. (8).

$$\begin{aligned}\hat{IRI}_{i0} = &135.28 - \left(0.65 + 0.085 Nc + 0.082 Fc - 0.017 Rt + 0.07 En\right) \times IRI_c \\ &- 1.85 Thk - 6.91 Mill\end{aligned} \tag{8}$$

The random-effects linear regression model can be estimated with the feasible generalized least squares (FGLS) method [14]. In the estimation of post-overlay IRI progression model with balanced panel data, the Lagrange Multiplier (LM) test [15] was conducted to check whether a random effects model is better than the pooled OLS model. Based on the estimation, the null hypothesis of the LM test is rejected, indicating that a random effects linear regression model is preferred. In addition, the first-order time-series correlation coefficient of error term (ρ) in post-overlay IRI regression model is identified as 0.66. All the estimated variables in the model are statistically significant within a 95% confidence level. The random effects post-overlay IRI progression model with correction for first-order autocorrelation is presented in Tab. 3.

Tab. 3. Post-overlay IRI progression model

Variable description	Coefficient	t statistic
Constant	-0.0153	-1.64
standard deviation for random parameter	(0.1445)	(7.16)
Pavement structure		
HMA overlay thickness	-0.0025	-10.92
Structural deflection	0.0594	14.22
Structural number	-0.0023	-2.58
Bound subbase	-0.0161	-10.97
Fine-grained subgrade	0.0034	3.62
Subsurface drainage	-0.0030	-2.33
Pavement performance before asphalt overlay		
Extensive-fatigue-cracking	0.0056	5.84
Traffic characteristics		
Annual average daily ESAL and time	0.0103	31.07
Climatic factors		
Wet freeze climate zone	0.0062	6.08
Maximum temperature	0.0731	16.75
Annual average freezing index	0.0105	9.89
Number of observations	4,050	
R-squared	0.582	
Adjusted R-squared	0.581	

Based on Tab. 3, the IRI after t overlay years can be predicted by incorporating the as-built IRI into the post-overlay IRI progression model. The average value of IRI after t overlay years ($\overline{IRI}_{it}$) can be calculated in Eq. (9).

$$\overline{IRI}_{it} = \overline{IRI}_{i0} \times \exp\left[\begin{pmatrix} -0.0025Thk + 0.0594Df - 0.0023Sn - 0.0161Bd \\ +0.0034Fn - 0.0030Dn + 0.0056Ft + 0.0103Es \\ +0.0062Wf + 0.0731Mt + 0.0105Fz \end{pmatrix} \times t\right] \tag{9}$$

where Thk is overlay thickness (inches), Df is the average deflection (mm), Sn is a high structure 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 ESAL), 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).

E. Discussion of Results

a. Asphalt Overlay Design Factors

Overlay thickness is one of the most important asphalt overlay design factors in rehabilitation policy. Based on the IRI drop model, Asphalt overlay thickness significantly affects the as-built roughness of overlaid pavements. To be specific, the as-built IRI of overlaid pavements would decrease by an average of 1.8 inches/mile with 1-in increase of asphalt overlay. This is perhaps because thicker overlays typically involve more lifts, which provide a contactor more opportunity to improve pavement smoothness [7]. Based on post-overlay IRI progression model, the roughness progression rate would decrease with the increase of overlay thickness. This is because thicker asphalt overlays reduce bending and vertical shear stress under traffic loads and reduce the temperature variation in the overlaid pavements. In addition, thicker asphalt overlays are more effective than thinner asphalt overlays in delaying the occurrence and deterioration of reflection cracking. When the IRI critical value for asphalt overlay is 170 inches/mile and all the other factors are set at their mean values, the effect of asphalt overlay thickness on post-overlay IRI progression is illustrated in Fig. 4. As can be seen, the overlay thickness can affect both as-built IRI and post-overlay IRI progression rate. In addition, the effect of overlay thickness on post-overlay IRI progression magnifies with the increased number of years after asphalt overlay.

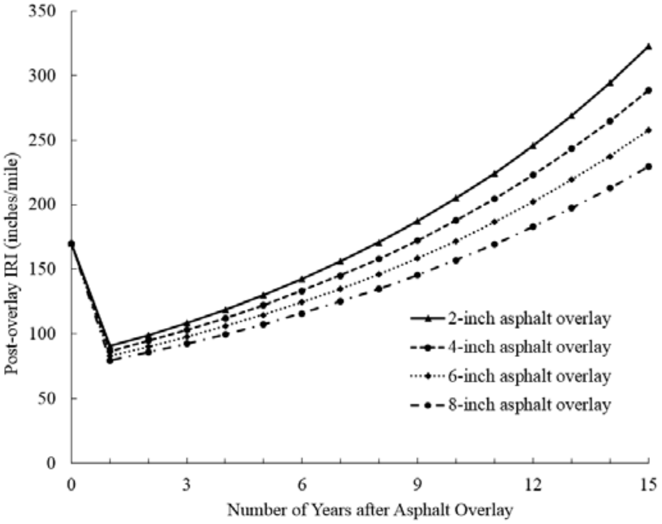

Fig. 4. Effect of overlay thickness on IRI progression

Milling operation has great ability to remove a variable thickness of existing pavement material and reduce the observable distresses of existing pavement [13, 16]. Based on IRI drop model, the effect of milling operation on the reduction of IRI is random rather than fixed. The mean value and standard deviation of IRI drop due to milling operation are 6.9 inches/mile and 0.3 inches/mile, respectively. Based on the distribution of the random parameter, milling operation would improve the smoothness of as-built overlaid pavements for nearly all roadway sections. However, due to unobserved heterogeneity, the magnitude of effect of milling operation on the reduction of as-built IRI varies from one roadway section to another. When the IRI critical value for asphalt overlay is 170 inches/mile and all the other factors are set at the mean value, the effect of milling operation on post-overlay IRI progression is illustrated in Fig. 5. As can be seen, the milling operation can only improve the as-built smoothness of overlaid pavements. Milling operation does not affect post-overlay IRI progression.

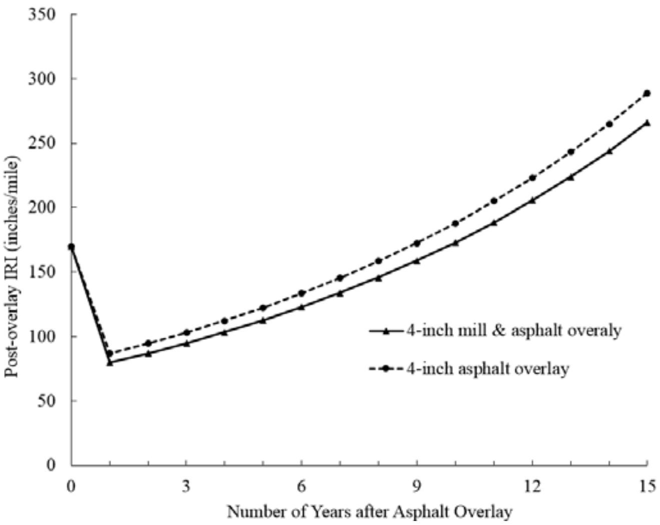

Fig. 5. Effect of milling operation on post-overlay IRI progression

In the study, asphalt overlay material types include virgin asphalt mixes and recycled asphalt mixes. In the sample data, the recycled overlay material consists of 30% recycled asphalt mixes. Based on IRI drop model and post-overlay IRI progression model, relative to the virgin asphalt mixes, the application of recycled asphalt mixes does not affect either IRI drop or post-overlay IRI progression rate.

b. Existing Pavement Performance

Based on the IRI drop and progression models, the existing pavement condition has a significant effect on its corresponding overlaid pavement roughness progression. To be specific, the pre-treatment IRI has a random effect on the reduction of IRI due to asphalt overlay. On average, the IRI drop value due to asphalt overlay would be about 65% of existing pavement IRI. However, the specific ratio of drop value to pre-treatment IRI varies from one overlay project to another. In addition, if the area of fatigue cracking on existing pavement exceeds 10% of total lane area, the average ratio of IRI drop to pre-treatment IRI would increase by 8%. While, if the rut depth of existing pavement exceeds 10 mm, the average ratio of IRI drop to pre-treatment IRI would decrease by 1.7%. This is because asphalt overlay activity can directly reduce fatigue cracking to zero. If an existing pavement has extensive fatigue cracking, it means that a high proportion of existing pavement roughness incurred by fatigue cracking will be addressed by implementing asphalt overlay. However, if existing pavement suffer severe rutting, the variance of overlaid pavement surface layer thickness and as-built initial rut depth would be large.

Based on the post-overlay IRI progression model, the pre-treatment IRI and severe rutting do not have significant effects on post-overlay roughness progression rate. However, the pavement roughness progression would accelerate if the existing pavement has extensive fatigue cracking. This is because the reflection cracking will be more likely to appear on overlaid pavement surface if the existing pavement has extensive fatigue cracking.

c. Existing Pavement Structure

In the study, the structural deflection is quantified by the average falling weight deflectometer (FWD) deflection at the center of a 9-kip load plate on the as-built pavement. The structural strength of pavement sections is also evaluated with the structural number (SN) based on layer thickness and layer coefficients. The layer coefficients for calculating SN are listed as follows: asphalt concrete-0.42; asphalt-treated base-0.35; and aggregate base-0.14 [11]. The asphalt layer thickness is the sum of existing asphalt layer thickness and asphalt overlay thickness. Since the SN only applies to the pavement layers above the subgrade, the maximum FWD deflection is not highly correlated with structure number. Based on the IRI progression model, the post-overlay roughness progression rate would decrease when the structure number of overlaid pavement exceeds five.

Relative to overlaid pavements with granular subbase, overlaid pavements with asphalt or cement treated subbase would decrease the post-overlay roughness progression rate. This is because, relative to granular subbase, the bound subbase are more likely to increase the overall structural strength of overlaid pavement. The existence of subsurface drainage was also identified to reduce post-overlay IRI progression rate. The similar finding is also found in the previous study [17]. In addition, the fine-grained subgrade type was found to accelerate post-overlay IRI progression. Because the profile of overlaid pavements with fine-grained soils is more likely to change with environmental effects (e.g., frost heave and swelling) than those with coarse-grained soils, especially in wet freeze climate zone.

d. Traffic and Environmental Characteristics

The post-overlay roughness progression rate increases significantly with an increase of annual average daily traffic. In addition, wet-freeze climate zone, annual average freeze index, and average daily maximum temperature in July are three climate factors affecting post-overlay IRI progression rate. This is perhaps because the overlaid pavement structure is more likely to suffer repeated volume changes due to freezing and thawing in the wet-freeze climate zone.

F. Summary

This chapter quantified the effects of asphalt overlay design factors and other associated causal factors on as-built pavement roughness and long-term pavement roughness progression. Fifteen years' post-overlay IRI data for 271 asphalt overlay projects were extracted from the long-term pavement performance database. Random parameters linear regression and random effects linear regression were conducted to develop a roughness drop model and a post-overlay roughness progression model, respectively. Based on the discussion of results, the major findings were summarized as follows.

- Relative to the virgin asphalt mixes, the application of 30% recycled asphalt mixes does not affect either as-built IRI or future IRI progression rate.
- Relative to thin asphalt overlay, thick asphalt overlay can reduce as-built pavement roughness and the rate of pavement roughness progression. The as-built pavement roughness would decrease by about 1.8 inches/mile with 1-in increase of asphalt overlay thickness.

- Milling operation would improve the smoothness of as-built pavement for nearly all roadway sections. However, due to unobserved heterogeneity, the magnitude of effect of milling operation on the reduction of as-built IRI varies from one roadway section to another. On average, the milling operation can reduce the as-built pavement roughness by about 6.9 inches/mile.
- Existing pavement condition has a significant effect on its corresponding overlaid pavement roughness progression. On average, the IRI drop value due to asphalt overlay would be about 65% of existing pavement IRI. In addition, the rate of overlaid pavement roughness progression would be larger if the existing pavement has extensive fatigue cracking.
- Granular subbase, fine-grained subgrade, subsurface drainage, wet-freeze climate zone, maximum temperature in July, annual average freezing index were identified to have significant effect on post-overlay roughness progression.

III. LIFE CYCLE ENVIRONMENTAL AND ECONOMIC IMPACTS OF DIFFERENT PAVEMENT OVERLAY STRATEGIES

A. Goal and Scope Definition

The research objective is to evaluate the environmental and economic impacts of different overlay strategies over a 40-year analysis period in a case study. As shown in Tab. 4, sixteen pavement overlay strategies analyzed in this study are built upon an existing flexible pavement originally constructed by the Florida Department of Transportation (FDOT). The general roadway segment information, existing pavement structure, existing pavement performance, traffic characteristics, climatic factors, and construction project information for these overlay projects are summarized in Tab. 5. The functional unit is a 10-km long, 3.7-m wide overlay system over the outer lane of an existing asphalt pavement. The construction schedules for these asphalt overlay strategies are based on the post-overlay roughness progression model and the pavement rehabilitation trigger value (IRI_c = 170 inches/mile). The specific construction schedules for different rehabilitation strategies are shown in Fig. 6.

Tab. 4. Design of different asphalt overlay strategies

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

(note: 1 inch = 25.4 mm)

Tab. 5. 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-course-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)	17,000
	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

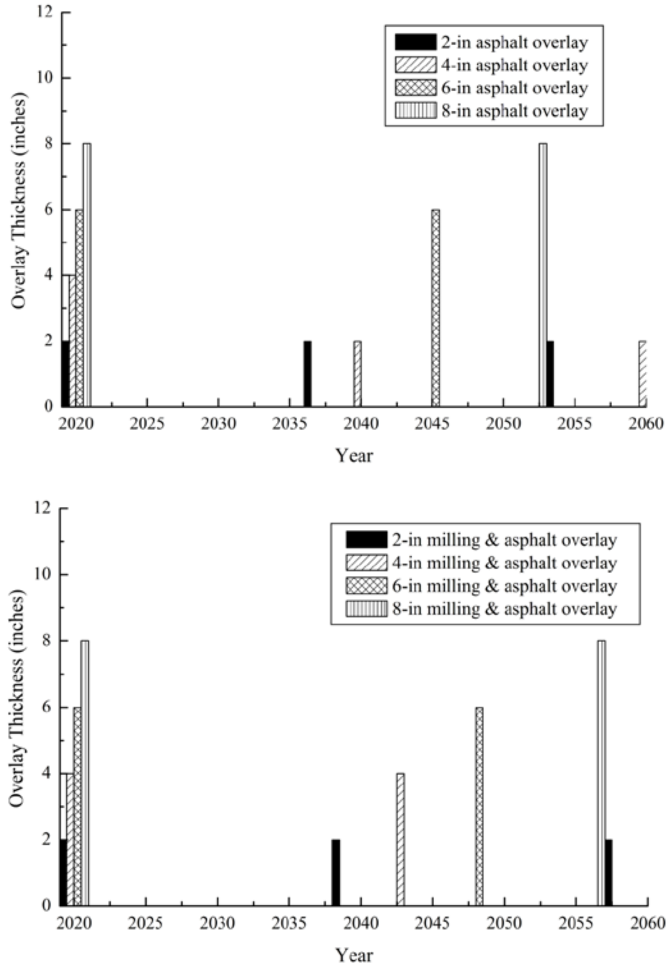

Fig. 6. Construction schedule of different overlay strategies

B. *Integrated LCA-LCCA Model*

The life-cycle environmental and economic impacts of different pavement overlay strategies are evaluated using an integrated LCA-LCCA approach, as illustrated in Fig. 7.

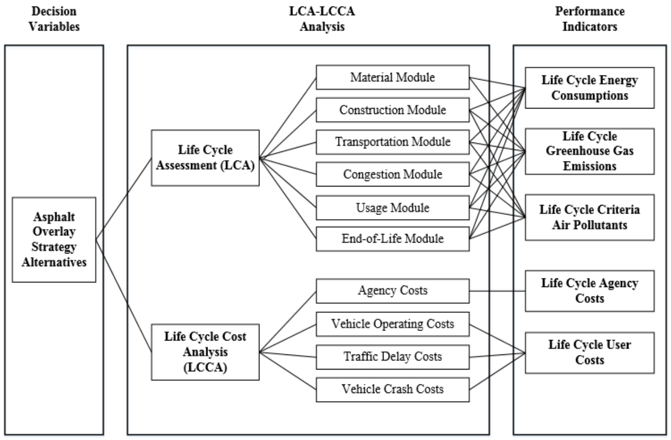

Fig. 7. An integrated LCA-LCCA approach for pavement overlay strategies

a. *Life Cycle Assessment*

The material module of a pavement LCA includes raw material acquisition and material processing in the process of pavement overlay activities. Different pavement overlay strategies may change the type and the amount of material consumed in construction. In this study, the construction materials include Type SP-12.5 Superpave hot mix asphalt (HMA), Type SP-19.0 Superpave HMA, and rapid-set emulsified asphalt tack coat (RS-1) [18]. The number of layers for HMA spreading and compression can be determined with tack coat guidelines [19]. To provide a good interface bonding condition between pavement lifts [20], based on the tack coat guidelines, the application rate of tack coat is set as 0.11 gallons per square yard. In material manufacturing process, the environmental impacts of 1-in type SP-12.5 HMA overlay, 1-in type SP-19.0 HMA overlay, and 1-layer RS-1 tack coat on 10-km long, one-lane pavement are summarized in Tab. 6, Tab. 7, and Tab. 8, respectively. Since reclaimed asphalt pavement (RAP) can reduce the use of virgin aggregates and virgin asphalt binders in the production of asphalt mixtures, the environmental impact in the material phase would decrease when 30% RAP material is applied.

Tab. 6. Environmental impact of 1-in Type SP-12.5 in material phase

Environmental indicator	Unit	Manufacturing
Global warming potential	kg CO2 eq	143,148.41
Acidification potential	kg SO2 eq	1,304.74
Human health (HH) particulate	kg PM2.5 eq	86.91
Smog potential	kg O3 eq	12,913.70
Total primary energy	MJ	8,651,327.50

Tab. 7. Environmental impact of 1-in Type SP-19.0 in material phase

Environmental indicator	Unit	Manufacturing
Global warming potential	kg CO2 eq	141,394.57
Acidification potential	kg SO2 eq	1,282.31
Human health (HH) particulate	kg PM2.5 eq	85.48
Smog potential	kg O3 eq	12,658.15
Total primary energy	MJ	8,462,122.11

Tab. 8. Environmental impact of 1-layer RS-1 tack coat in material phase

Environmental indicator	Unit	Manufacturing
Global warming potential	kg CO2 eq	2,675.01
Acidification potential	kg SO2 eq	22.71
Human health (HH) particulate	kg PM2.5 eq	1.56
Smog potential	kg O3 eq	287.96
Total primary energy	MJ	183,206.76

The construction module includes equipment use and energy use at the construction site. The fuel types of all construction equipment are assumed to be diesel. The fuel consumption and production rate of the equipment used in pavement overlay activities are summarized in Tab. 9.

The transportation module accounts for transport of materials and equipment to and from the construction site. Based on the system definition of overlay projects in Tab. 5, the average distance from plant to site, the average distance from equipment depot to site, and the average distance from site to stockpile are assumed to be 100 km. Then, the environmental impacts due to equipment use and transportation in the construction process of 1-in type SP-12.5 overlay on the functional unit is illustrated in Tab. 10. In addition, the environmental impacts for 1-in and 2-in milling operation on the functional unit can be calculated and summarized in Tab. 11.

Tab. 9. A list of equipment during overlay activity

Equipment	Fuel Consumption		Production Rates	
	Value	Unit	Value	Unit
Asphalt Paver	0.0620	l/tonne	1215	tonne/day
Asphalt Remixer	3.6409	l/tonne	8.30	tonne/hour
Black Topper	0.0009	l/m^2	10000	m^2/hourr
Cold In-Place Recycler	0.0438	l/tonne	1713	tonne/hour
Compactor	0.0237	l/tonne	2,726	tonne/day
Heating Machine	1.1307	l/tonne	8.30	tonne/hour
HMA Transfer	0.0935	l/tonne	1,215	tonne/day
Roller	0.0533	l/tonne	1,215	tonne/day
Concrete Truck	3.7854	l/m^2	60	m^3/day
Dump Truck	0.2271	l/tonne	1,000	tonne/day
Water Truck	0.0114	l/m^2	20,00	m^2/day
Pavement Breaker	0.1345	l/m^2	1,000	m^2/day
Diamond Grinder	1.0759	l/m^2	125	m^2/day
Milling Machine	0.4203	l/m^3	40	m^3/hour

Tab. 10. Environmental impact due to 1-in overlay construction activity

Name	Unit	Equipment	Transport
Global Warming Potential	kg CO2 eq	335,181.4	18,832.7
Acidification Potential	kg SO2 eq	958.5	181.1
HH Particulate	kg PM2.5 eq	52.9	10.0
Smog Potential	kg O3 eq	21,815.6	5,713.9
Total Primary Energy	MJ	4,932,599.7	274,568.5

Tab. 11. Environmental impact due to 1-in and 2-in milling operation

Name	Unit	Equipment	Transport
1-in milling on functional unit			
Global Warming Potential	kg CO2 eq	131,433.5	19,300.5
Acidification Potential	kg SO2 eq	1246.0	185.6
HH Particulate	kg PM2.5 eq	70.0	10.3
Smog Potential	kg O3 eq	39,877.4	5,855.9
Total Primary Energy	MJ	1,916,217.4	281,389.3
2-in milling on functional unit			
Global Warming Potential	kg CO2 eq	132,564.6	38,125.8
Acidification Potential	kg SO2 eq	1274.9	366.7
HH Particulate	kg PM2.5 eq	70.6	20.3
Smog Potential	kg O3 eq	40,220.6	11,567.5
Total Primary Energy	MJ	1,932,708.1	555,849.6

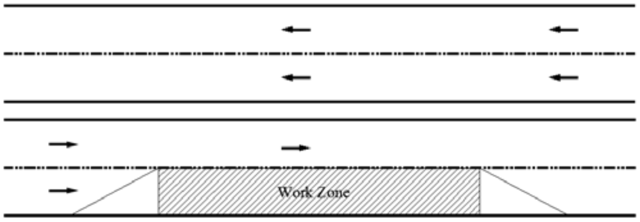

Fig. 8. Partial closure (with right lane closed) work zone

The congestion module accounts for the environmental impacts due to construction-related traffic congestion, traffic delay, and traffic detour. In this study, as shown in Fig. 8, the type of work zone is partial closure with the right lane closed, resulting in no disruption to traffic in the opposite direction. The traffic volumes of passenger car, light-duty truck, and heavy-duty truck account for 88%, 10%, and 2% of total traffic volume, respectively. The traffic capacity and the average vehicle speed in the normal state are 2,200 vehicles per hour and 120 km/h, respectively. Based on Jiang’s model [21], the mean speeds during uncongested state and congested state in partial closure work zone is 95 km/h and 50 km/h, respectively. The mean traffic capacity in partial closure work zone is 1,537 vehicles per hour. Vehicle queues occur when traffic flow is higher than the traffic capacity of the work zone. Based on the above inputs, the vehicle delay, detour rate, and queue length in the partial closure work zone can be estimated with QuickZone software. Once vehicle delay and congestion due to construction activity are identified, they are coupled with fuel consumption and vehicle emissions to quantify their environmental impacts. The vehicle fuel economy varies when its driving state changes. The city drive cycle is used to calculate the fuel consumption during congestion (i.e., stop-and-go driving) and detour modes. The highway drive cycle is used to model the normal traffic flow during uncongested traffic periods. The specific fuel economy and emission factors can be extracted from various sources [22, 23]. Based on the calculated traffic flow difference between normal condition and construction periods, the fuel consumption and environmental buderns are calculated with Eq. (10).

$$Y_{total} = VMT_{queue}Y_{queue} + VMT_{workzone}Y_{workzone} + VMT_{detour}Y_{detour} - VMT_{normal}Y_{normal} \qquad (10)$$

where Y_i is the value of different environmental indicators, such as, fuel usage (L/mile) or emission value (g/mile), VMT_i is the total miles traveled by vehicles (mile), i is a scenario index, representing total, waiting in queue, passing through the work zone, taking detour, or operating under normal conditions.

The usage module quantifies the environmental impacts of vehicle operations within the analysis period. Different pavement overlay strategies change vehicle fuel economy by affecting the pavement roughness progression. Based on

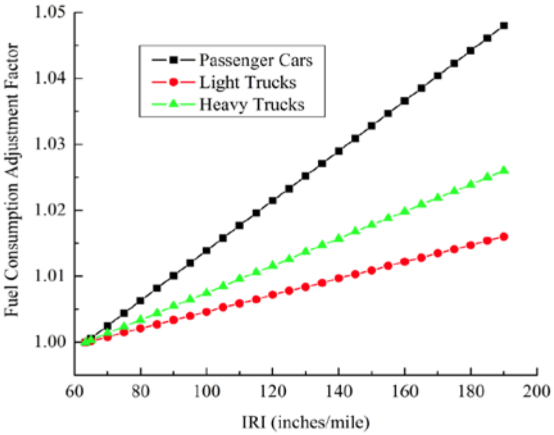

Fig. 9. Effect of pavement roughness on vehicle fuel consumption

Chatti and Zaabar's calibration of the HDM-4 model [24], the effect of pavement roughness on vehicle fuel consumption under the average speed of 120 km/h is shown in Fig. 9. In addition, based on the proposed post-overlay roughness progression model in Chapter II, the effect of different overlay strategies on pavement roughness progression over the 40-year analysis period is shown in Fig. 10. As we can see, increasing pavement roughness leads to more vehicle fuel consumption and pollutant emissions. The usage module of the LCA model captures the difference of environmental impacts between driving on an overlaid pavement and on an ideally smooth pavement (IRI=63 inches/mile).

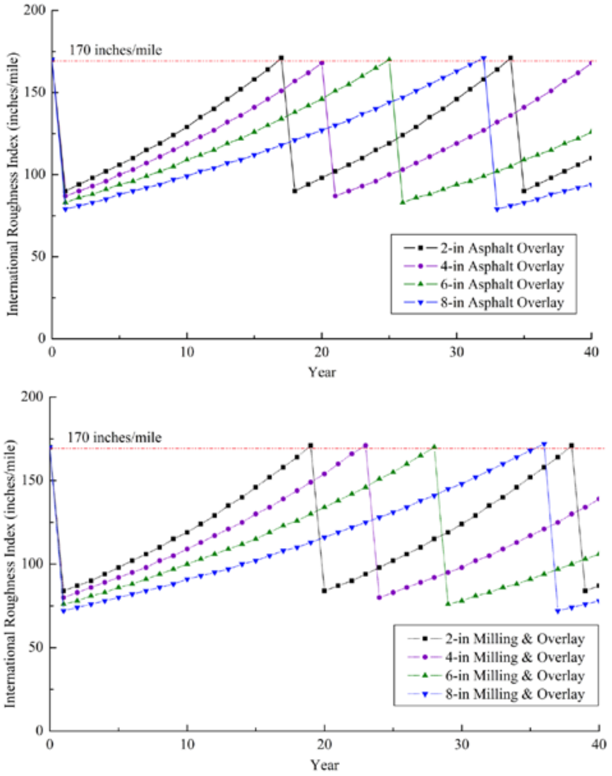

Fig. 10. Effect of different overlay strategies on pavement roughness

The activities at the end of pavement service life can be classified into three types: (1) removal of materials and disposal in landfills; (2) pavement in-place reuse; and (3) pavement material recycling. Because the pavement sections are most likely to remain in place at the end of the analysis period, a "cut-off" allocation method is used to assign no environmental impacts to the end-of-life module for all pavement overlay strategies in comparison.

b. Life Cycle Cost Analysis

The LCCA procedure consists of selecting an analysis period, selecting a discount rate, selecting a measure of economic worth, and determining monetary agency costs and user costs. The selected analysis period is the same as the analysis period for life cycle assessment. The discount rate is assumed to be 3%. The present worth expressing all costs and benefits over the analysis period in terms of their equivalent values in the initial year of the analysis period is selected as the measure of economic worth. Agency costs include all costs (e.g., material costs, equipment use fee, labor costs, temporary traffic control, and mobilization cost) incurred directly by the highway agencies over the analysis period. The residual value of the recent overlay pavement structure at the end of the analysis period is deducted from agency costs.

The other information associated with agency cost calculation is illustrated as follows. The temporary traffic control cost is assumed to be 1,000 \$/day. The mobilization cost is estimated as 2% of the total project cost. The equipment use fee and labor costs are included into the unit cost of paving overlay materials. The unit cost of asphalt mixture is 400\$/tonne [25]. The unit cost of RS-1 tack coat is 650 \$/tonne. The densities of asphalt mixture and tack coat are 2.460 tonne/m^3 and 1.015 tonne/m^3, respectively. The relationship between the unit cost of milling operation and the milling depth can be calculated with Eq. (11).

$$y = 0.0927x^2 + 0.4409x + 1.8287 \tag{11}$$

where y is the unit cost (\$) of milling operation per square yard, x is the milling depth (inches).

The durations of construction activities for different overlay strategies over analysis period are summarized in Tab. 12.

Tab. 12. Construction durations for different overlay strategies

Scheme	Overlay Frequency	Construction Duration Per Time	Total Construction Time
1	3	15 days	45 days
2	3	15 days	45 days
3	3	8 days	24 days
4	3	8 days	24 days
5	2	19 days	38 days
6	2	19 days	38 days
7	2	12 days	24 days
8	2	12 days	24 days
9	2	23 days	46 days
10	2	23 days	46 days
11	2	16 days	32 days
12	2	16 days	32 days
13	2	26 days	52 days
14	2	26 days	52 days
15	2	19 days	38 days
16	2	19 days	38 days

The user costs include vehicle operating costs (VOC), user delay costs and vehicle crash costs. The vehicle operating costs are estimated as the monetary value of extra fuel consumption of vehicle traveling on an overlaid pavement relative to that on an ideally smooth pavement. Based on the FHWA report [26], the rates of delay cost for passenger cars, light-duty trucks, and heavy-duty trucks are 11.58 \$/veh-hr (vehicle hour), 18.54 \$/veh-hr, and 22.31\$ /veh-hr, respectively. The delay cost rates are in 1996 dollars and updated to 2020 dollars in the LCCA model using the rate of inflation. The vehicle crash costs are estimated with the increased crash risk due to overlay construction activities. The increased crash risk costs for construction-related work-zone traffic and detour traffic are estimated as 0.22\$/vehicle-miles-traveled (VMT) and 0.15\$/VMT, respectively [27].

C. Results and Discussions

The environmental impact performance indicators include global warming potential (GWP), acidification potential (AP), human health (HH) particulate, smog potential (SP), and total primary energy consumption (TPE). The GWP is expressed on an equivalency basis relative to CO_2, where GWP is 1 for CO_2, 25 for CH_4, and 298 for N_2O [28]. The AP of air or water emission is calculated on the basis of its SO_2 equivalent effect. The HH particulate includes the particulate matter of various sizes (PM_{10} and $PM_{2.5}$). The smog potential is expressed on a mass of equivalent O_3, which is a product of interactions of volatile organic compounds (VOCs) and nitrogen oxides (NOx). Since sulfur dioxide (SO_2), particulate matter (PM), and nitrogen dioxide (NO_2) are criteria air pollutants (CAP), the CAP can be calculated as the sum value of AP, HH, and SP. In addition, since feedstock energy stored in asphalt mixture can be harvested later during the recycling process, it is not included in the total primary energy consumption. Thus, the TPE, GWP, and CAP are three environmental impact indicators reflecting life-cycle energy consumption, life-cycle GHG emissions, and life-cycle air pollutants of different overlay strategies.

a. Energy Consumption

The energy consumption in material module, construction module, transportation module, congestion module, and usage addition module of different overlay strategies is illustrated in Fig. 11. Life cycle energy consumptions for 2-in, 4-in, 6-in, and 8-in asphalt overlay strategies (i.e., schemes 3, 7, 11, and 15) are 2.37×10^5 GJ, 2.53×10^5 GJ, 2.54×10^6 GJ, and 2.77×10^6 GJ, respectively. The three major LCA modules for energy consumption are usage module, construction module, and material module.

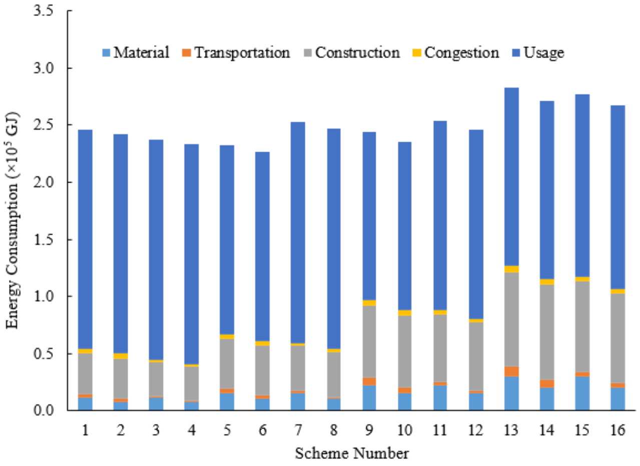

Fig. 11. Life cycle energy consumption of different overlay strategies

Relative to the conventional HMA overlay, the inclusion of 30% RAP for 2-in and 8-in asphalt overlays reduces the life cycle energy consumption by 1.6% and 3.7%, respectively. For 4-in asphalt overlay in the study, inclusion of 30% RAP material can reduce the total energy consumption by 5.19×10^3 GJ. This is because the inclusion of 30% RAP materials does not affect pavement roughness progression. In addition, they can reduce the use of virgin aggregates and virgin asphalt binders in the production of HMA. In this study, the optimum overlay strategy consuming the least amount of energy in the analysis period is 4-in milling and asphalt overlay, and 30% RAP materials.

b. Greenhouse Gas Emissions

The greenhouse gas (GHG) emissions in different LCA modules for different overlay strategies are illustrated in Fig. 12. Similar to energy consumption, the three major LCA components for GHG emissions are also usage module, construction module, and material module. Life cycle GHG emissions for 2-in, 4-in, 6-in, and 8-in asphalt overlay strategies are 1.63×10^7 kg CO_2 eq, 1.73×10^7 kg CO_2 eq, 1.75×10^7 kg CO_2 eq, and 1.92×10^7 kg CO_2 eq, respectively.

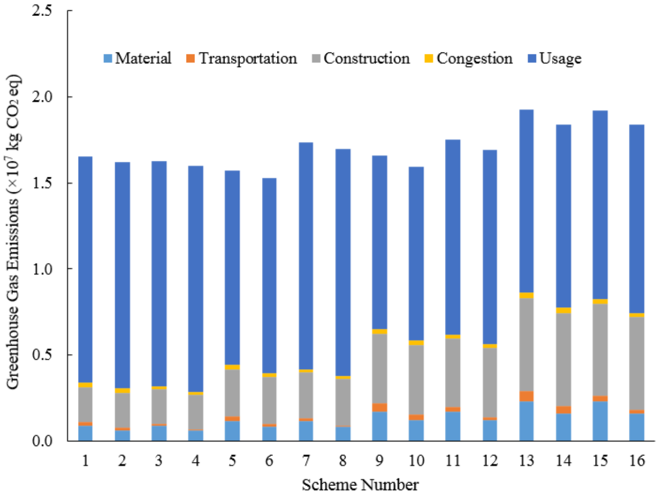

Fig. 12. Life cycle GHG emissions of different overlay strategies

Relative to the conventional HMA overlay, the inclusion of 30% RAP for 2-in and 8-in asphalt overlay reduces the life cycle GHG emissions by 1.8% and 4.1%, respetively. For 4-in asphalt overlay in the study, inclusion of 30% RAP material can reduce the total GHG emissions by 3.93×10^5 kg CO_2 eq. In this study, the optimum overlay strategy emitting the least amount of greenhouse gases in the analysis period is also 4-in milling and asphalt overlay, and 30% RAP materials.

c. Criteria Air Pollutants

The criteria air pollutants can harm human health and environment, and cause property damage. The criteria air pollutants in different life cycle stages for different overlay strategies are illustrated in Fig. 13.

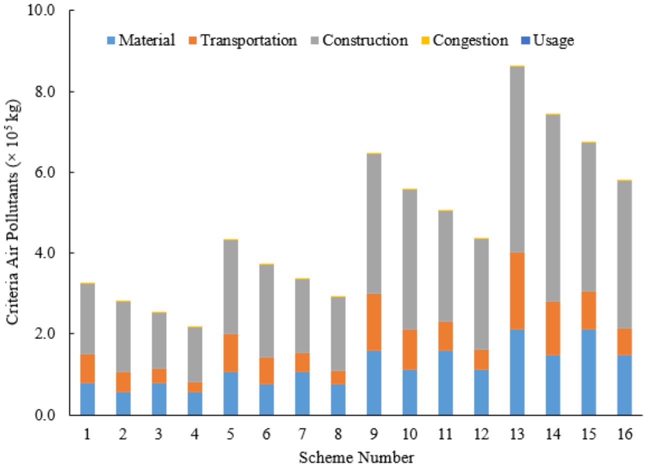

Fig. 13. Life cycle criteria air pollutants of different overlay strategies

As can be seen, the three major LCA components for criteria air pollutants are construction, material, and congestion. The criteria air pollutants increase monotonically with the increase of overlay thickness. The milling operation would increase the emission of criteria air pollutants. Conversely, the inclusion of RAP materials can benefit public health and environment by reducing the criteria air pollutants. The optimum scheme of asphalt overlay strategies for minimizing the criteria air pollutants over analysis period is Scheme 4 (2-in asphalt overlay, and 30% RAP).

d. Life Cycle Cost

The life cycle costs for different overlay strategies are shown in Fig. 14. The life cycle costs for 2-in, 4-in, 6-in, and 8-in asphalt overlay strategy are 8.11 dollars, 10.84 dollars, 11.93 dollars, and 12.94 million dollars, respectively. The two major components of life cycle costs are highway agency costs and usage phase vehicle operating costs.

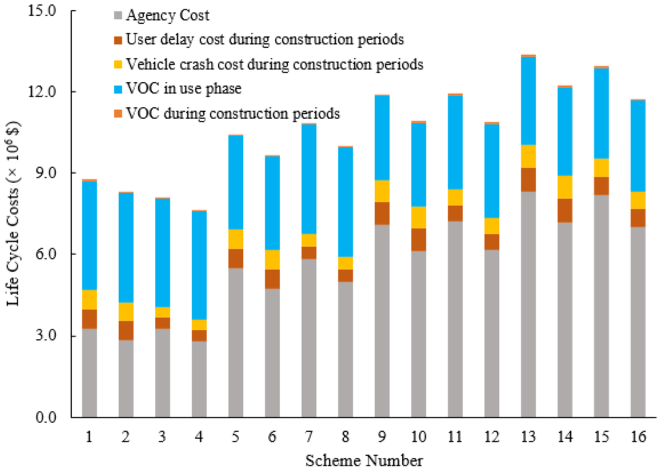

Fig. 14. Life cycle costs of different overlay strategies

Relative to the conventional HMA overlay, the inclusion of 30% RAP for 2-in and 8-in asphalt overlay reduces the life cycle costs by 5.8% and 9.3%, respectively. For the 4-in asphalt overlay in the study, inclusion of 30% RAP material can save the total life cycle cost by 848,500 dollars. The optimum asphalt overlay strategy with the minimum life cycle cost is 2-in asphalt overlay and 30% RAP.

D. Sensitivity Analysis

The results discussed above assume a baseline scenario which has no traffic volume growth or fuel economy improvements over time. Traffic volume growth will affect a series of factors, such as post-overlay pavement roughness progression rate, overlay schedule, total construction periods, vehicle miles travelled, congestion, user delay, detour traffic, and construction-related traffic flow. In addition, due to the updated vehicle structure design and development of fuel-saving technologies, the vehicle fuel efficiency will continue to increase with time. Fuel economy improvements will directly decrease traffic-related energy consumption. In recent years, several researchers have performed the sensitivity analysis on traffic volume growth rate and fuel economy [5, 6]. However, few researchers have analyzed the effect of traffic volume levels on life cycle sustainability of overlay strategies. In this study, three different traffic levels (e.g., high-, medium-, and low-volume traffic) are incorporated in the life cycle modeling analysis. The AADT in high-volume traffic scenario, medium-volume traffic scenario (baseline scenario), and low-volume scenario are assumed to be 87,000 vehicles/day, 17,000 vehicles/day, and 1,700 vehicles/day. The truck percentage and traffic growth rate are assumed to be 12% and 0%, respectively.

The effect of traffic level on life cycle energy consumption of different overlay strategies is illustrated in Fig. 15.

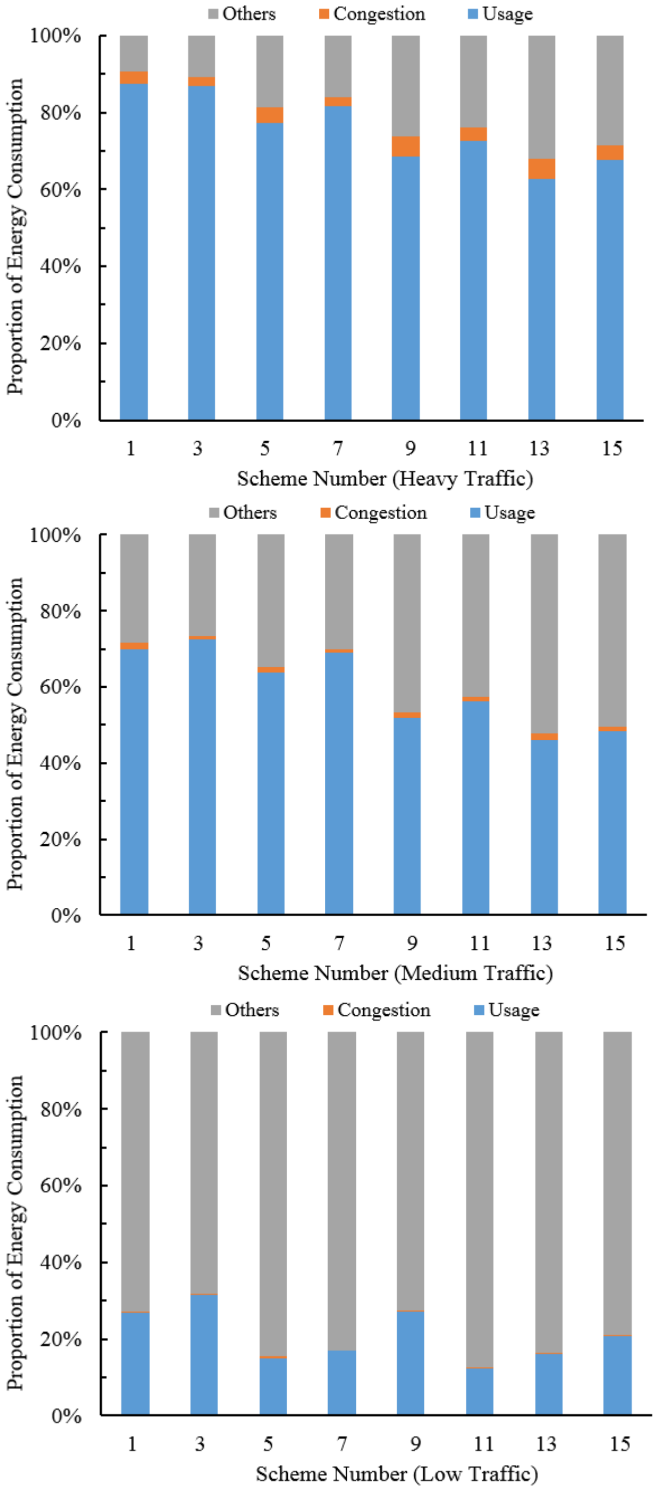

Fig. 15. Life cycle energy consumption of different overlay strategies

As can be seen, in the heavy traffic level scenario, congestion module accounts for 2%-5% of total life cycle energy consumption. The average ratio of use phase energy consumption to total energy consumption for all overlay strategies under the heavy traffic, medium traffic, and low traffic are 76%, 60%, and 21%, respectively. Under the medium- and high-volume traffic, the major LCA module for life cycle energy consumption is the usage module in different overlay strategies. While, under the low-volume traffic, material and construction phases in overlay activities play a major role in life cycle energy consumptions. The optimum overlay strategy for reducing life cycle energy consumption in the medium and heavy traffic scenarios is 4-in milling and asphalt overlay and 30% RAP. While, under the low traffic, the optimum overlay strategy for reducing life cycle energy consumption is 2-in asphalt overlay and 30% RAP.

The effect of traffic level on life cycle GHG emissions of different overlay strategies is shown in Fig. 16.

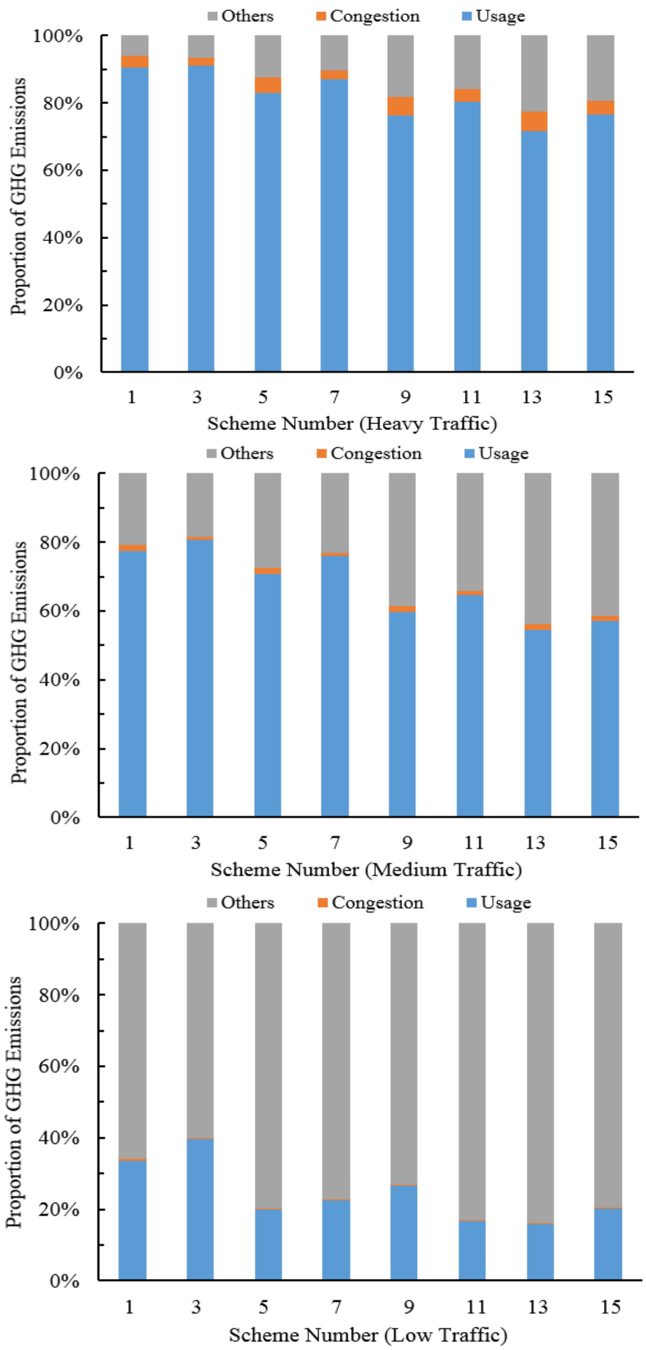

Fig. 16. Life cycle GHG emissions of different overlay strategies

As can be seen, the proportion of life cycle energy consumptions in the usage phase of LCA decreases significantly when the traffic level changes from heavy to low. Under a medium or heavy traffic, the major component of life cycle GHG emissions for different overlay strategies is the usage module. While, under the low traffic, the major components of life cycle GHG emissions are the material module and the construction module.

The effect of traffic level on life cycle costs of different overlay strategies is shown in Fig. 17.

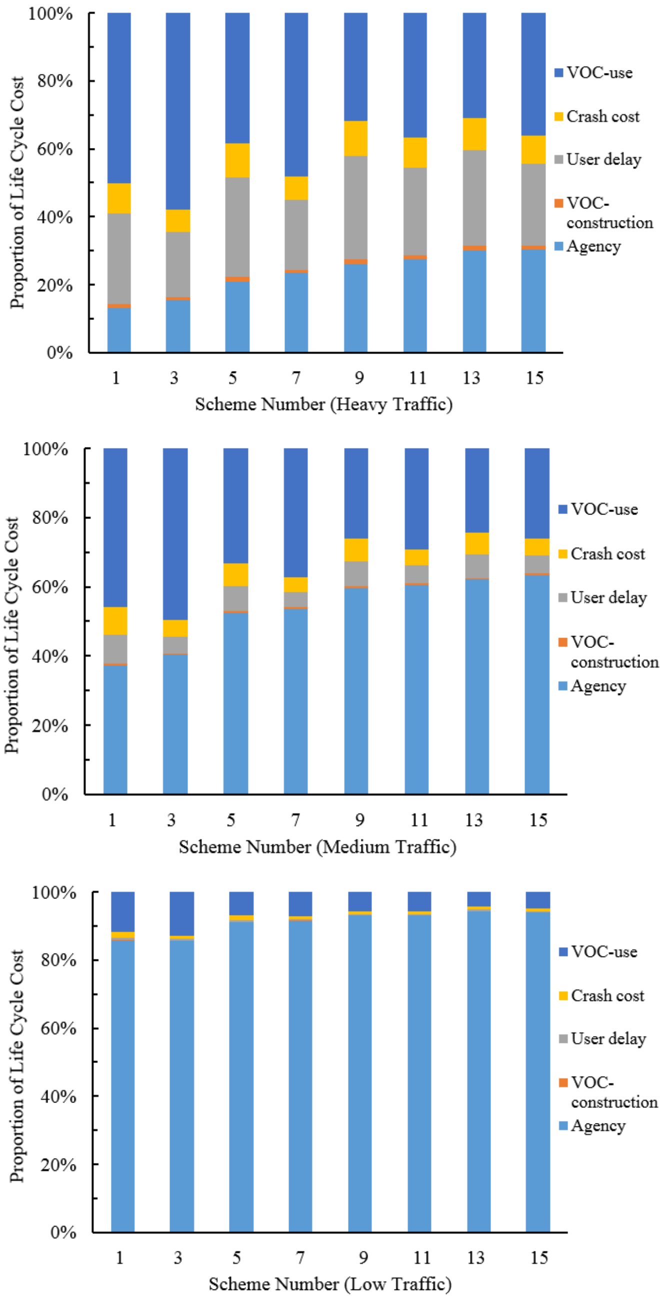

Fig. 17. Life cycle costs of different overlay strategies

As can be seen, under a heavy traffic, the critical components of overlay system life cycle costs are vehicle operating costs in the use phase, user delay costs during construction periods, and highway agency costs. While, under a low- or medium-volume traffic, highway agency costs account for a major component of life cycle costs for all overlay strategies. The optimum overlay strategy for reducing life cycle costs is “2-in asphalt overlay with 30% RAP” under all traffic conditions.

Since the usage phase is a major component in life cycle environmental impacts for all overlay strategies under medium or heavy traffic, a sensitivity analysis on IRI trigger value is performed with the optimum overlay strategy. When the IRI trigger value for pavement overlay reduces from 170 inches/mile to 120 inches/mile, the life cycle environmental impact of the overlay strategy (i.e., 4-in milling and asphalt overlay and 30% RAP) in the usage phase reduces by 30%. However, the overlay frequency during the analysis period will increase if the IRI trigger value reduces from 170 inches/mile to 120 inches/mile. Thus, the construction-related environmental impacts and costs will also increase significantly. The optimization analysis of IRI trigger value for overlay is necessary in the future study, especially for heavy-traffic highways.

E. Summary

This chapter quantifies the life cycle environmental and economic effects of different overlay strategies using an integrated LCA-LCCA approach. Based on the discussion of results, the major findings are summarized as follows.

- Pavement surface roughness effects, construction activity, and material production are the greatest contributors to life cycle energy consumption and greenhouse gas emissions for asphalt overlay projects. The usage-phase vehicle operating costs and agency costs are two major components of life cycle costs for asphalt overlay projects.
- The application of 30% RAP material can significantly improve the environmental and economic sustainability of overlaid pavements. In this study, compared to the conventional HMA overlay, the inclusion of 30% RAP for 4-in asphalt overlay reduces the life cycle energy consumption by 2.5%, GHG emissions by 2.8%, criteria air pollutants by 13.8%, and life cycle costs by 7.8%.
- Based on the sustainability goal of life cycle energy consumption and GHG emissions, the optimum overlay strategy for the case study is 4-in milling and asphalt overlay with 30% RAP. While, based on the sustainability goal of life cycle criteria air pollutants and costs, the optimum overlay strategy is 2-in asphalt overlay with 30% RAP.
- Under a medium or heavy traffic, the major LCA module for life cycle environmental impacts of overlay projects is the usage module. While, under a low traffic, the major LCA modules are the material module and the construction module. Under the low traffic, the highway agency cost is a dominant factor in life cycle cost analysis for all overlay projects.
- IRI trigger value has a significant impact on life cycle environmental impacts of different overlay strategies in the usage module. To be specific, under a medium or heavy traffic condition, the life cycle environmental impacts of the overlay strategy (4-in milling and asphalt overlay with 30% RAP) in the usage phase can reduce by 30% when the IRI trigger value reduces from 170 inches/mile to 120 inches/mile.

IV. MULTI-OBJECTIVE OPTIMIZATION FOR IDENTIFYING SUSTAINABLE PAVEMENT OVERLAY STRATEGY

A. Introduction

An ideal pavement overlay strategy for a highway segment is one that maintains the pavement condition at a high level of service, but requires a low use of resources and minimum impact on the public users and environment. However, many of these objectives conflict with each other. In practice, highway agencies mainly focus on optimizing pavement performance under a budget constraint. An LCCA is usually conducted to identify the optimum pavement overlay strategy. The environmental impacts of pavement overlay activities, however, are typically ignored in scheduling pavement overlay activities.

In recent years, several researchers have attempted to incorporate the environmental impacts into an optimization analysis of scheduling pavement overlay activities. For example, in 2010, Zhang et al. considered the environmental impacts of overlay activities by treating the environmental damage costs as inputs for the LCCA. Then, a dynamic programming approach is used to identify the optimum overlay strategy [29]. However, the optimum overlay strategy obtained with the concept of environmental damage costs is largely sensitive to the marginal damage costs. A change in the marginal damage costs will result in a different optimum overlay strategy. In addition, identifying the marginal damage costs for different types of air pollutants is rather difficult. To avoid finding marginal damage costs, in 2012, Giustozzi et al. eliminated the different unit measures of performance indicators for rehabilitation strategies by rescaling them to the base rehabilitation scenario. Then, a multi-attribute indicator for each rehabilitation strategy was calculated as the weighted sum value of different performance indicators [30]. Finding the value of weighting factors, however, is highly subjective and not straightforward.

To address the uncertainty issue of environmental damage costs or weighting factors, a multi-objective optimization framework is proposed for identifying sustainable pavement overlay strategies. To be specific, first, asphalt overlay design factors, post-overlay roughness models, and IRI threshold values are combined to identify the feasible overlay strategies. Then, an integrated LCA-LCCA approach is used to link these feasible strategies to environmental impacts and economic costs. Finally, a multi-objective optimization approach is used to link the decision variables (e.g., overlay thickness, IRI threshold) to multiple performance indicators (i.e., life-cycle energy consumption, GHG emission, criteria air pollutants, agency costs, and user costs). Instead of transforming the multi-objective functions into a composite objective function (i.e., weighted-sum of objectives), an optimization algorithm (e. g., genetic algorithm [GA]) may be used to identify the Pareto-optimal overlay strategies. Based on the highway agencies’ specific objective, the optimum overlay strategy may be selected from the Pareto-optimal set.

The remainder of this chapter is structured as follows. The multi-objective optimization framework is illustrated in

Section B. The formulation of optimum asphalt overlay strategy based on multiple life-cycle performance measures (i.e., environmental and economic performance indicators) in each module is presented in Section C. Finally, Section D discusses the potential applications of the proposed approach.

B. Multi-objective Optimization Framework

The process of optimizing systematically and simultaneously a collection of objective functions is identified as multi-objective optimization. In this study, the collection of objective functions include the life-cycle energy consumption, GHG emissions, criteria air pollutants, agency costs, and user costs. The decision variables include IRI trigger value for overlay and asphalt overlay design factors. Because applications of 30% RAP material have been identified to reduce both life cycle environmental impacts and life cycle costs, it is not considered as a decision variable in the framework. The detailed multi-objective optimization framework is shown in Fig. 18.

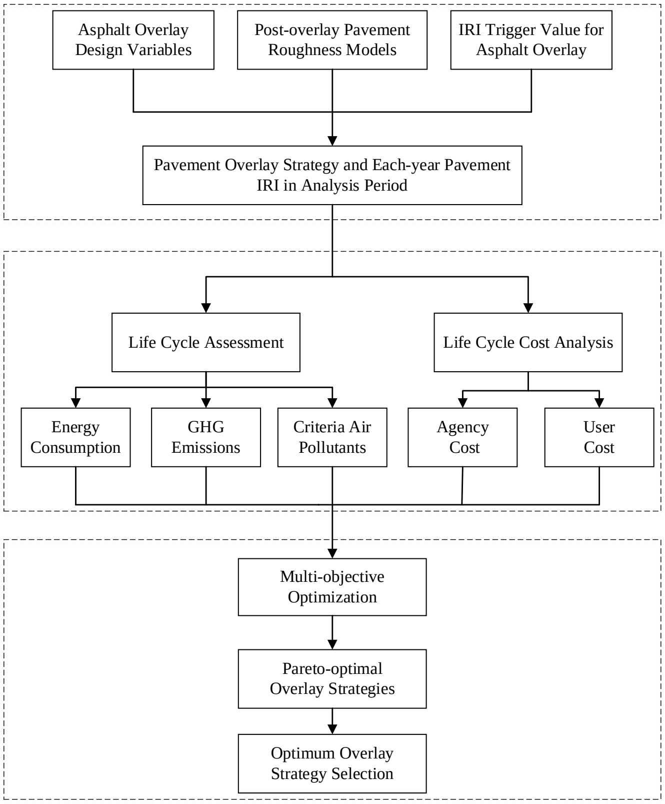

Fig. 18. Multi-objective optimization for sustainable overlay strategy

As can be seen in Fig. 18, the objective of the upper part of the framework is to formulate the feasible pavement overlay strategies. Supposing the IRI of an existing pavement is 170 inches/mile, once the asphalt overlay design variables are determined, the as-built IRI model (Eq. 8) and post-overlay IRI model (Eq. 9) may be used to predict the pavement roughness progression under the combined effects of traffic loads and environmental factors. When the post-overlay IRI reaches the IRI trigger value, another overlay activity may be scheduled. Finally, the pavement IRI for the asphalt overlay strategy in each year can be identified.

The middle part of the framework aims to link the decision variables (e.g., IRI trigger value and overlay thickness) with multiple life-cycle performance measures. To be specific, life cycle environmental impacts and economic costs would be determined in each life-cycle module (Fig. 2).

The lower part of the framework aims to identify the Pareto optimal solutions for the multiple-objective optimization problem. Then, based on the specific preference of highway agencies, the optimum asphalt overlay strategy can be selected from the Pareto optimal set. The detailed procedures and equations for each part of framework are illustrated in the following section.

C. Procedures and Equations

a. Multi-objective Optimization Problem

The multi-objective optimization problem (MOOP) for the study is formulated in Eq. (13).

$$\begin{aligned} &Find: x=[x_1,x_2,x_3]^T \\ &Min.: f(x)=[f_1(x), f_2(x), f_3(x), f_4(x), f_5(x)]^T \\ &S.t.: 0.5 \le x_1 \le 8; x_2 = 1/0; 63 \le x_3 \le 170 \end{aligned} \tag{13}$$

where, x_1 is asphalt overlay thickness (inches), x_2 is a dummy variable to indicate whether milling operation is applied or not (1-milling and asphalt overlay, 0-asphalt overlay), x_3 is IRI trigger value for asphalt overlay. The lower bound and upper bound of the overlay thickness are 0.5 inches and 8.0 inches, respectively. The lower bound and upper bound of the IRI threshold are 63 inches/mile (an ideally smooth pavement) and 170 inches/mile (required level of service), respectively. $f_1(x)$, $f_2(x)$, $f_3(x)$, $f_4(x)$, $f_5(x)$ are life-cycle energy consumption, GHG emissions, criteria air pollutants, agency costs, and user costs for asphalt overlay strategies over the analysis period, respectively.

b. Life Cycle Environmental Performance Measures

To establish the explicit equations between life-cycle environmental performance indicators and asphalt overlay strategies, the functional unit and system definition should be firstly determined. For example, as shown in Section A of Chapter III, the functional unit is a 10-km long, 3.7-m wide overlay section on the outer lane of an existing asphalt pavement. Second, as shown in Tab. 6 through Tab. 11, with the defined functional unit, the relationships between the multiple life-cycle environmental performance indicators and 1-in asphalt overlay, 1-layer tack coat, 1-in milling operation in the material, construction, and transportation modules can be identified. Third, based on the specific asphalt overlay strategy, the asphalt overlay thickness, number of tack coat layers, milling depth, construction duration, pavement IRI for each year, number of overlay activities are determined over the analysis period. Fourth, the multiple environmental performance indicators in each module are identified for all feasible asphalt overlay strategies. Finally, the multiple environmental performance measures for each overlay strategy are determined over the analysis period.

c. Life Cycle Economic Performance Measures

To establish the explicit equations between life-cycle economic performance indicators and asphalt overlay strategies, the functional unit and the system definition should also be firstly determined. Second, based on the specific asphalt overlay strategy, the asphalt overlay thickness, number of tack coat layers, milling depth, construction duration, pavement IRI for each year, overlay time and frequency are determined over the analysis period. Third, the material costs, equipment use fee, labor costs, temporary traffic control cost, mobilization cost, construction-related delay cost and accident cost for each asphalt overlay activity are determined. Fourth, the IRI-related fuel consumption costs and the residual costs for each asphalt overlay strategy are identified. Finally, all these costs are combined by category and updated to the current monetary value.

d. Feasible Asphalt Overlay Strategies

In the study, as shown in Fig. 19, the feasible asphalt overlay strategies and each-year pavement IRI can be determined by incorporating the IRI trigger value and asphalt overlay design factors into the post-overlay IRI progression models.

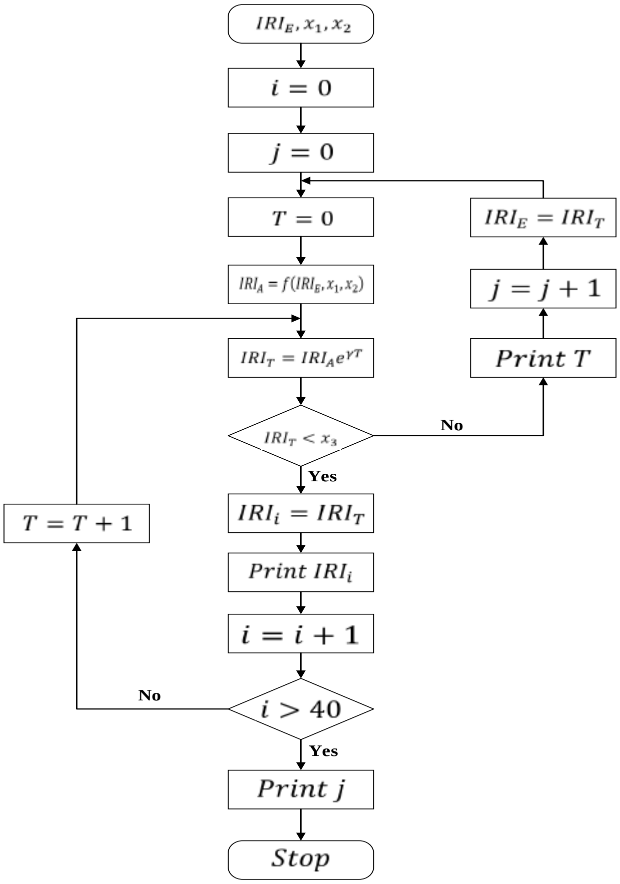

Fig. 19. Formulation process of asphalt overlay strategy over analysis period

The IRI_E represents the IRI of existing pavement before asphalt overlay. The IRI_A is the as-built pavement IRI after asphalt overlay [Eq. (8)]. The IRI_T is the post-overlay IRI at T years after asphalt overlay [Eq. (9)]. x_1, x_2, and x_3 are defined in Eq. (13). i represents the specific year in the analysis period. j represents the total overlay frequency. T represents the specific year in which overlay is performed.

D. Potential Applications

The multi-objective optimization framework is proposed to identify the sustainable asphalt overlay strategy. If the funding constraint and construction duration limitation are available, they can be represented as the constraints in Eq. (13).

E. Summary

This chapter proposes a multi-objective optimization framework for identifying sustainable pavement overlay strategy. The procedures and equations about implementing the framework are illustrated. To be specific, first, asphalt overlay design factors, post-overlay roughness models, and IRI threshold values are combined to identify the feasible overlay strategies. Then, an integrated LCA-LCCA approach is used to link these feasible overlay strategies to environmental impacts and economic costs. Finally, a multi-objective optimization approach is used to link the decision variables (e.g., overlay thickness, IRI threshold) to multiple performance indicators (i.e., life-cycle energy consumption, GHG emission, criteria air pollutants, agency costs, and user costs). Instead of transforming the multi-objective functions into a composite objective function (i.e., weighted-sum of objectives), a genetic algorithm (GA) may be used to identify the Pareto-optimal overlay strategies. Based on the highway agencies' specific objective, the optimum overlay strategy can be identified from the Pareto-optimal set.

V. CONCLUSIONS

The purpose of this research is to guide highway agencies to optimize flexible pavement overlay strategies using an integrated life cycle assessment (LCA) - life cycle cost analysis (LCCA) approach. In the study, a post-overlay IRI progression model was firstly developed to evaluate the effect of asphalt overlay design factors on pavement roughness progression. Then, by incorporating the proposed post-overlay IRI model in the integrated LCA-LCCA framework, the life cycle environmental and economic impacts of different overlay strategies were evaluated. Finally, a genetic-algorithm (GA) based multi-objective optimization framework was proposed for identifying the sustainable asphalt overlay strategy. Based on the analysis results, the major conclusions are summarized as follows.

- Asphalt overlay thickness and milling operation have significant effects on post-overlay pavement roughness progression. However, the inclusion of 30% reclaimed asphalt pavement (RAP) materials in asphalt overlay activities does not affect pavement roughness progression. Since RAP can reduce the use of virgin aggregates and virgin asphalt binders in the production of asphalt mixtures, the inclusion of RAP material can significantly improve the environmental and economic sustainability of overlaid pavements.
- For asphalt overlay projects, pavement surface roughness effects, construction activity, and material production are three major contributors to life cycle energy consumption and greenhouse gas (GHG) emissions. The usage phase vehicle operating costs and agency costs are two dominant factors in life cycle cost analysis of asphalt overlay projects.

- Traffic level has a significant effect on the proportion distribution of life cycle environmental impacts over different modules. When overlay projects are under a medium or heavy traffic, to minimize the life cycle energy consumption and GHG emissions, highway agencies can select the “4-in milling and asphalt overlay with 30% RAP” overlay strategy. While, if overlay projects are subject to a low traffic volume, the optimum pavement rehabilitation strategy is “2-in asphalt overlay with 30% RAP”.
- International roughness index (IRI) trigger value for pavement overlay activities is a key factor affecting the life cycle environmental and economic sustainability of overlaid pavements. To achieve the environmental and economic sustainability goal of pavement overlay strategies, further study is needed to develop an optimization framework for determining the optimum IRI trigger value and the optimum overlay strategy (i.e., overlay thickness, milling or not).
- The multi-objective optimization framework for identifying the sustainable asphalt overlay strategy is illustrated. First, asphalt overlay design factors, post-overlay roughness models, and IRI threshold values are combined to identify the feasible overlay strategies. Then, an integrated LCA-LCCA approach is used to link these feasible overlay strategies to environmental impacts and economic costs. Finally, a multi-objective optimization approach is used to link the decision variables to multiple performance indicators. Instead of transforming the multi-objective functions into a composite objective function (i.e., weighted-sum of objectives), a genetic algorithm (GA) may be used to identify the Pareto-optimal overlay strategies. Based on the highway agencies’ specific objective, the optimum overlay strategy may be selected from the Pareto-optimal set.

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