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LIFE CYCLE ASSESSMENT OF PAVEMENT OVERLAY SYSTEMS WITH FOCUS ON USAGE PHASE

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Keywords: Life cycle; Environmental impacts; Overlay system; Traffic delay; Usage; Recycling

Proposals for implementation:
None

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None

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DISCLAIMER

The contents of this work plan reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the University of South Florida or Florida Department of Transportation.

EXECUTIVE SUMMARY

A Life cycle assessment (LCA) model was constructed in this report to estimate and compare the environmental impacts of three overlay systems: portland cement concrete (PCC) overlay, hot mixture asphalt (HMA) overlay, and crack, seat, and overlay (CSOL). The LCA model consists of six modules: material module, distribution module, construction module, congestion module, usage module, and end of life (EOL) module, with efforts mainly focusing on the usage module. Through the study, several major conclusions were obtained. First, HMA overlay and CSOL overlay demand 109 and 64 percent more energy and emit 73 and 44 percent more greenhouse gas (GHG), respectively, than PCC overlay within a 40-year life cycle. Second, material module, congestion module, and particularly usage module contribute most to energy consumptions and air pollutant emissions. Third, traffic related energy consumptions and GHG are very sensitive to traffic growth and fuel economy improvement. Fourth, recycling 20 percent of waste HMA into new overlay could reduce the energy consumptions of HMA and CSOL options, but not enough to alter the ranks of the three alternatives.

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1. INTRODUCTION

Although still at a developing stage, life cycle assessment (LCA) of transportation infrastructures has attained increasing attention and significance among transportation communities, and its application has been practiced with continuous improvements. An LCA is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave. For example, a pavement overlay system, as studied in this report, includes energy consumptions, pollutants emissions, ecological and human health impacts, and so on. LCA can help avoid a narrow outlook on environmental concerns by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential impacts associated with identified inputs and releases, and by interpreting the results to make a more informed decision (EPA 2006). LCA was originated in the 1960's but not applied to transportation community until late 1990's (Häkkinen and Mäkelä 1996).

Two common approaches were applied in previous pavement LCA studies. One is process level LCA that traces energy consumptions and pollutant emissions within the life cycle of a pavement (Mroueh et al. 2000, Zapata and Gambatese 2005). The other is economical input-output (ECO-IO) LCA that couples IO models with sector-level environmental data to obtain estimates of the economy-wide environmental burdens (Horvath and Hendrickson 1998). A combination of these two approaches, aiming to capture their advantages, namely hybrid LCA model, has also been practiced by a few researchers (Park et al. 2003, Treloar et al. 2004).

Although with many endeavors in previous researches, LCA in pavement application is still at a premature stage and demands efforts to fill the gap of knowledge due to the complexity of a pavement system. Typically, a LCA model of pavement consists of the following components: material, construction, usage, maintenance and rehabilitation (M&R), and end of life (EOL) (Santero et al. 2010). However, most of the research efforts are not comprehensive enough to incorporate all the components. Nisbel et al. (2001) evaluated the life cycle inventory of portland cement concrete (PCC) and asphalt pavements with emphasis on material, construction, M&R, and EOL phases. The Athena Institute (2006) used Canadian data to assess the energy consumptions and global warming potentials (GWP) of concrete and asphalt roadways with various structure combinations, with its inventory limited to materials and M&R. Chan (2007) performed a LCA study on 26 pavement structures, and his outputs were raw material depletions, energy consumptions, and air emissions from materials, construction and M&R activities.

Although these studies provide valuable information for subsequent studies, the effort was insufficient to draw reliable conclusions for the study objectives because two most important elements in LCA models, usage and traffic congestion resulting from construction and M&R activities, had not been considered. Huang et al. (2009) suggested that additional fuel consumptions and pollutant emissions due to traffic delay during roadwork periods are significant. For studies including the usage phase, their conclusions are consistent: usage phase dominates the LCA outputs when traffic volume is high, or behaves as a counterpart to material component to be the most significant one in LCA models when traffic volume is low (Häkkinen and Mäkelä 1996, Stripple 2001, Treloar et al. 2004). Even with the incorporation of a usage phase, their studies still have room to improve: first, some of the studies are outdated and need data update; second, energy consumptions and air emissions due to congestions during construction and M&R periods should be included; third, the usage phase is not complete in these studies, with some significant parts missing.

To the author's knowledge, the most comprehensive LCA studies to date were carried out by Keoleian, G. A. et al. (2005) and Zhang et al. (2010). They considered the traffic congestions due to construction and M&R activities, and additional fuel consumption due to the effect of pavement roughness on fleet speed and pavement capacity, and hence jumped a big step compared with other studies. Nevertheless, these considerations are still insufficient. Usage phase is critical to any reliable LCA conclusions, which shall consider not only pavement roughness effect, but also pavement structure property effect, albedo, and carbonation for PCC pavements (Santero et al. 2010). Furthermore, EOL phase in their studies was simply deemed as landfill while practically, most hot mixture asphalt (HMA) is recycled and old PCC is crushed to substitute base course aggregates.

The objective of this research is to develop a comprehensive LCA model to enhance pavement overlay design and evaluate the long-term environmental performances of overlay systems by incorporating as many components as possible, with emphasis on usage phase.

2. METHODOLOGY

A LCA model is established to evaluate the environmental impacts of various overlay systems from raw material acquisition to overlay disposal. Different from some previous studies, this study separates distribution of materials as an individual component while combines construction and M&R activities together. Thus, the LCA model is divided into six modules: material production, construction and M&R (called construction in short), distribution, traffic congestion, usage, and EOL.

2.1. Functional Unit

Equivalent functionality shall be maintained for all candidates of a LCA model. For pavement, it means various pavement systems need to provide the same performance for the same traffic over a given period. A functional unit quantifies a standard amount to be compared between options that serve this function. In this study, the functional unit is defined as one kilometer overlay system over an existing PCC pavement with four lanes in two directions that would provide satisfactory performance over a 40-year period.

The structure of the existing PCC pavement consists of a 225 mm (9 in.) PCC layer and a 250 mm (10 in.) crushed aggregate base course. The PCC layer is at the end of its service life and demands rehabilitation to restore the serviceability, while the existing base course is assumed to perform well and can still work without intensive maintenance activities. The traffic conditions include an annual average daily traffic (AADT) of 70,000, with 8 percent of truck, and an annual traffic growth rate of 4 percent.

2.2. Rehabilitation Plans

Three frequently adopted replacement options in Florida State are considered:

- Remove and replace the existing pavement with PCC (hereafter called the PCC option). Remove the existing PCC, keep the existing base and subgrade in place, and repave with new PCC of 250 mm (10 in.). Use diamond grinding as a periodic rehabilitation strategy.
- Remove and replace the existing pavement with HMA (hereafter called the HMA option). Remove the existing PCC, keep the existing base and subgrade in place, and repave with new HMA of 225 mm (9 in.). Use a mill-and-fill (removal of the HMA surface with a cold planer and replacement of the same depth of new HMA) as a periodic rehabilitation strategy.
- Crack, seat, and overlay (hereafter called the CSOL option). Crack and seat (Halil et al. 2005) the existing PCC pavement and then overlay it with 125 mm (5 in.) HMA. Use a mill-and-fill as a periodic rehabilitation strategy.

The three pavement overlay designs followed the Florida Department of transportation (FDOT) pavement design manual (2008, 2009) and were verified by the Mechanistic-Empirical Pavement Design Guide (MEPDG) software (2011) using Florida local weather data.

The California Department of Transportation (CALTRANS) reported that the average life of a diamond-grind surface is between 16 to 17 years (2005), so a diamond grinding action will be applied to the PCC option every 16 years. For the other two options, a HMA mill-and-fill plan commonly used by previous research with a frequency of every 16 years (Weiland and Muench, 2010; Zhang et al, 2010) is employed in this study. Table 1 lists the information of the three overlay system options

TABLE 1 Structural Design and Rehabilitation Schedules for Three Options

PCC	**HMA**	**CSOL**
Geometric (Width) Information of One Direction		
Inner paved shoulder: 1.2 m	Inner paved shoulder: 1.2 m	Inner paved shoulder: 1.2 m
Main lane: 3.6 m×2	Main lane: 3.6 m×2	Main lane: 3.6 m×2
Outside paved shoulder: 2.7 m	Outside paved shoulder: 2.7 m	Outside paved shoulder: 2.7 m
Structural (Thickness) Specifications		
250 mm (10 in.) PCC	50 mm (2 in.) HMA	50 mm (2 in.) HMA
	75 mm (3 in.) HMA	75 mm (3 in.) HMA
	100 mm (4 in.) HMA	
250 mm (10 in.) existing crushed aggregate		225 mm (9 in.) cracked and seated existing PCC
Existing subgrade	Existing subgrade	Existing subgrade
Rehabilitation Techniques		
Diamond grind to restore surface smoothness (CALTRANS, 2005).	Remove and replace (mill-and-fill) the top 1.8 in. (45 mm) every 16 years (Weiland and Muench, 2010).	Remove and replace (mill-and-fill) the top 1.8 in. (45 mm) every 16 years (Weiland and Muench, 2010).
Rehabilitation Schedules		
Year 2010: reconstruction Year 2026: diamond grind	Year 2010: reconstruction Year 2026: mill-and-fill	Year 2010: reconstruction Year 2026: mill-and-fill
Year 2042: diamond grind	Year 2042: mill-and-fill	Year 2042: mill-and-fill

3. LCA MODEL

To assess the environmental impacts of pavement overlay systems, a system of LCA model is developed, as shown in Figure 1. The LCA functionality is fulfilled by six components, including material module, distribution module, construction module, congestion module, usage module, and EOL module, with various supplementary models attached to the corresponding modules.

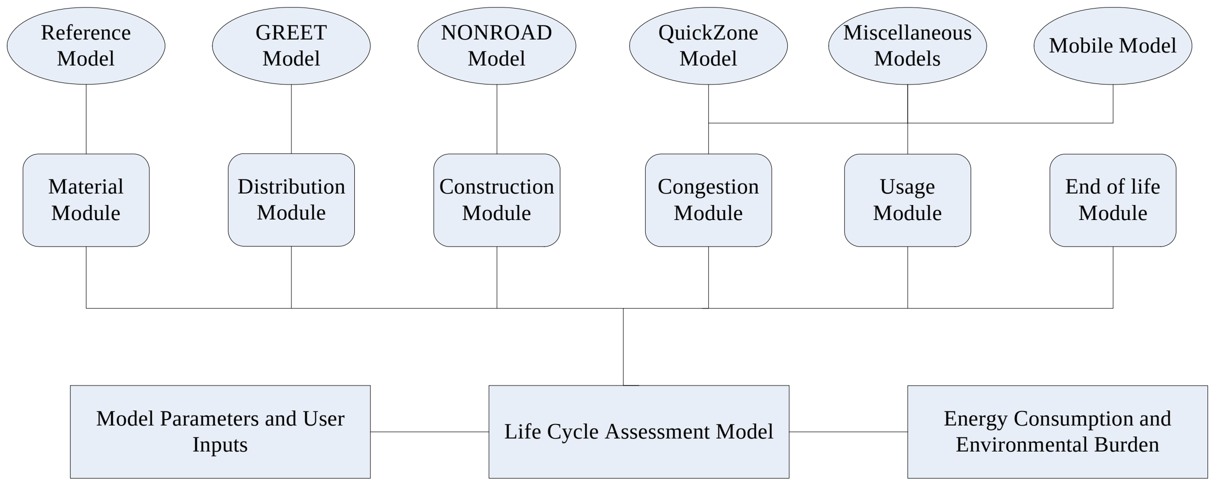

FIG.1 Logic Relationship Among Various Components

3.1. Material, Distribution, and Construction Modules

Material consumption is modeled with data from various reference sources, including the Portland Cement Association (PCA) (Marceau et al. 2007), the Swedish Environmental Research Institute (Stripple 2001), and the Athena Institute (AI) (2006). The data fields supplied by these references are total energy consumptions (including feedstock energy in this study for HMA) and discharged environmental pollutants, including carbon dioxide emissions (CO_2), carbon monoxide emissions (CO), methane, nitrogen oxide emissions (NOx), sulfur oxide emissions (SO_X), volatile organic compound (VOC), and particulate matter (<10μm) (PM10).

The distribution module is closely linked to the material module and EOL module. All the materials, equipments, and wastes are transported by a combination of roadway, railway, and waterway. Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET 2010) model was used as a source of data for the amounts of fuel and electricity production, truck transportation, tie and dowel bar production, and natural gas burned in the HMA tack truck. Versions 1.8 (for material transportation) and 2.7 (for steel production) of the GREET model were used.

Emission data for all nonroad construction and vehicular equipments were obtained from the EPA NONROAD2008 model (2008). For each piece of construction equipment, an estimate of the engine horsepower was made on the basis of one or two typical machines. NONROAD2008 provides emission factors for various ranges of horsepower. For all cases, NONROAD2008 data were specified to Florida State for a year-long average, and all equipment used diesel fuel for non-road equipment.

The inventories associated with the material, distribution, and construction modules are listed in Table 2 through 4.

TABLE 2 Remove and Replace with PCC Process and Data

Number	Task	Data Source	Item	Quantity per km for one direction
Remove and Replace with PCC				
1	Breaking existing PCC	NONROAD	300-hp off-road truck	1.4 h
			175-hp crushing processing	
2	Load broken PCC	NONROAD	300-hp excavator	33.3 h
3	Waste PCC truck transport[a]	GREET 1.8	Heavy-heavy trucks[e]	157950 tonne-km
4	Utility excavator[b]	NONROAD	300-hp excavator	8.0 h
5	Base grading	NONROAD	175-hp grader	2.1 h
6	Base compaction	NONROAD	300-hp roller	1.7 h
7	PCC production	PCA (2007)	25 MPa, no slag, no fly ash	6660 tonne
8	PCC mix transportation[a]	GREET 1.8	Heavy-heavy trucks	166500 tonne-km
9	PCC placing and spreading	NONROAD	300-hp surfacing equipment	57.4 h
10	Dowel-tie bar production[c]	GREET 2.7	Low-grade steel	55 tonne
11	Dowel-tie bar transportation	GREET 1.8	Heavy-heavy trucks	4125 tonne-km
12	PCC paving and bar placement	NONROAD	300-hp paver	57.4 h
13	Texture-curing	NONROAD	75-hp surfacing equipment	51.6 h
14	PCC saw cutting	NONROAD	75-hp concrete-industrial. saw	15.0 h
Diamond Grinding (to be accomplished at years of 2026 and 2042)				
1	Diamond grinder[d]	NONROAD	600-hp surfacing equipment	17.0 h
			100-hp surfacing equipment	
2	Grinder transport[d]	GREET 1.8	Heavy-heavy trucks	4162 tonne-km

NOTE: [a]The distance from work zone to PCC recycling facility or PCC plant is 25 km.

[b]Assumed to accomplish small work items at about 8 h per km of one direction.

[c]Epoxy, stainless, or other coating or cladding is not included.

[d]Must travel 25 km to the work zone. Need three passes per lane. Weight is 32 tonne.

[e]The heavy–heavy truck class can haul up to 18 tonne (20 ton) of cargo, and remains the same meaning in following contents.

TABLE 3 Remove and Replace with HMA Process and Data

Number	Task	Data Source	Item	Quantity per km for one direction
Remove and Replace with HMA				
1-6	Same as in Table 2			
7	Bitumen production	Stripple (2001) AI (2006)	Grade B60, 50/70 pen	306 tonne
8	Bitumen transportation	GREET 2.7	Heavy-heavy trucks	24480 tonne-km
9	Crushed aggregate production[a]	Stripple (2001) AI (2006)		5695 tonne
10	Crushed aggregate transportation	GREET 1.8	Heavy-heavy trucks	56950 tonne-km
11	HMA production[b]	Stripple (2001) AI (2006)		6001 tonne
12	HMA transportation[c]	GREET 1.8	Heavy-heavy trucks	150025 tonne-km
13	Emulsion production	Stripple (2001)	CSS-1 emulsion tack coat	12.5 tonne
14	Material transfer vehicle	NONROAD	300-hp surfacing equipment	33.7 h
15	HMA paver	NONROAD	300-hp paver	33.7 h
16	Breakdown rolling	NONROAD	Two 300-hp rollers	67.6 h
17	Finish rolling	NONROAD	100-hp roller	33.7 h
18	Tack coat application	GREET 1.8	Medium-heavy vehicled	504 tonne-km
19	Tack coat truck heater	GREET 1.8	Small natural gas turbine	528 MJ of propane
45 mm (1.8 in.) HMA mill and fill (to be accomplished at years of 2026 and 2042)				
1	Milling machine	NONROAD	750-hp surfacing equipment	13.5 h
2	RAP transportation[c]	GREET 1.8	Heavy-heavy vehicle	30007 tonne-km
3	Street sweeping	GREET 1.8	Medium-heavy trucksd	77.2 tonne-km
4	Sweeper auxiliary engine	NONROAD	100-hp cement-mortar mixer	0.8 h
5	Bitumen production	Stripple (2001) AI (2006)	Grade B60, 60/70 pen	61.7 tonne
6	Bitumen transportation	GREET 1.8	Heavy-heavy vehicle	4933 tonne-km
7	Crushed aggregate production[a]	Stripple (2001) AI (2006)		1147 tonne
8	Crushed aggregate transportation	GREET 1.8	Heavy-heavy vehicle	11470 tonne-km
9	HMA production[b]	Stripple (2001) AI (2006)		1209 tonne
10	HMA transportation[c]	GREET 1.8	Heavy-heavy vehicle	30228 tonne-km
11	Emulsion production	Stripple (2001) AI (2006)	CSS-1 emulsion tack coat	6.6 tonne
12	Material transfer vehicle	NONROAD	300-hp surfacing equipment	11.4 h
13	HMA paver	NONROAD	300-hp paver	11.4 h
14	Breakdown rolling	NONROAD	Two 300-hp rollers	22.6 h
15	Finish rolling	NONROAD	100-hp roller	11.4 h
16	Tack coat application	GREET 1.8	Medium-heavy vehicled	160 tonne-km
17	Tack coat truck heater	GREET 1.8	Small natural gas turbine	151 MJ of propane

NOTE: [a] A hundred percent crushed aggregate was used in HMA.

[b] 5.1 percent binder, no reclaimed asphalt pavement (RAP) in baseline case.

[c] Distance from work zone to the PCC recycling facility, HMA plant, or RAP storage area is 25 km.

[d] The medium–heavy truck class can haul up to 7.2 tonne (8 ton) of cargo, and remains the same meaning in following contents.

TABLE 4 CSOL Process and Data

Number	Task	Data Source	Item	Quantity per km for one direction
Remove and Replace with HMA				
1-6	Same as in Table 2			
7	Bitumen production	Stripple (2001) AI (2006)	Grade B60, 50/70 pen	179 tonne
8	Bitumen transportation	GREET 1.8	Heavy-heavy truck	14321 tonne-km
9	Crushed aggregate production[a]	Stripple (2001) AI (2006)		3331 tonne
10	Crushed aggregate transportation	GREET 1.8	Heavy-heavy truck	33310 tonne-km
11	HMA production[b]	Stripple (2001) AI (2006)		3510 tonne
12	HMA transportation[c]	GREET 1.8	Heavy-heavy truck	150025 tonne-km
13	Emulsion production	Stripple (2001) AI (2006)	CSS-1 emulsion tack coat	8.3 tonne
14	Material transfer vehicle	NONROAD	300-hp surfacing equipment	22.5 h
15	HMA paver	NONROAD	300-hp paver	22.5 h
16	Breakdown rolling	NONROAD	Two 300-hp rollers	45.1 h
17	Finish rolling	NONROAD	100-hp roller	22.5 h
18	Tack coat application	GREET 1.8	Medium-heavy vehicle	336 tonne-km
19	Tack coat truck heater	GREET 1.8	Small natural gas turbine	352 MJ of propane
45 mm (1.8 in.) HMA mill and fill (to be accomplished at years of 2026 and 2042)				
Same as in Table 3				

NOTE: [a]A hundred percent crushed aggregate was used.

[b]5.1 percent binder, no reclaimed asphalt pavement (RAP) in baseline case.

[c]Distance from work zone to the PCC recycling facility, HMA plant, or RAP storage area is 25 km.

One limitation of this inventory is that maintenance activities (e.g., patching, joint repairing, and crack sealing) between major rehabilitation plans are not considered because these maintenance activities are generally small and isolated.

3.2. Congestion Module

Traffic delay brought by construction and rehabilitation activities has significant influences on energy consumptions and pollutant emissions compared with those under normal vehicular operations, and thus is included in the scope of this study. The changes in traffic flow, traffic delay, and queue length are estimated using the QuickZone model (McTrans, version beta 0.99, 2001). In the baseline scenario, the annual traffic growth rate is zero percent. For construction activities, it is assumed that the two lanes in each direction are both closed so that all traffic takes detour, with a speed reduction from 104 km/h (65 mph, highway speed) to 60 km/h (40 mph, local speed), and a longer travel distance of 2.4 km (1.5 mi). For the two rehabilitation activities, it is assumed that only one lane will be temporarily closed. Under this scenario, the outputs from QuickZone model reveal that 27 percent of traffics take detour, and the remaining traffic causes a 1 km (0.62 mi) queue.

Once vehicle delays due to construction and maintenance events are determined, they are coupled with fuel consumptions and vehicle emissions to measure their environmental impacts. Two drive cycles, city one and highway one, are used to determine the fuel economy and to calculate the fuel consumptions, with the former one describing the fuel consumptions of stop-and-go vehicular behaviors during construction and rehabilitation period and the latter one characterizing normal conditions. Vehicle fuel economy is taken from the U.S. EPA fuel economy guide (U.S. EPA 2006). CO_2 is calculated by the fuel consumptions (Emission Facts, 2005), based on the assumption that all passenger cars burn gasoline and trucks combust diesel. Other vehicle emissions are calculated at varying traffic speeds using U.S. EPA's MOBILE 6.2 software, which supplies the tailpipe emissions and evaporative emissions on a per year basis through 2050 (U.S. EPA 2002). Two Florida localized data were used as inputs: the average annual temperature range and Reid vapor pressure.

The outputs of the fuel consumptions and environmental burdens are calculated as the differences between those of construction and rehabilitation periods and those of normal operations, which are given by:

$$Y_{total} = VMT_{queue} \times Y_{queue} + VMT_{workzone} \times Y_{workzone} + VMT_{\det our} \times Y_{\det our} - VMT_{normal} \times Y_{normal} \tag{1}$$

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

Because traffic volume is an important determinant of traffic delay, estimating future trends of traffic can play a large role in determining the environmental impacts of construction and rehabilitation projects. This will be addressed in the sensitive analysis section.

3.3. Usage Module

While the former module describes the additional environmental burdens brought by construction and rehabilitation activities, the usage module focuses on the fuel consumptions and pollutants emission due to vehicle operations within the scope period. This section is of great importance and complexity compared with the former module.

3.3.1 IRI Effect

Only the side effects released by the vehicles due to increased pavement surface roughness are considered within this sub-section.

Three major factors pose great influences on LCA inventory, including: traffic volume, fuel economy, and pavement roughness. The traffic volume factor will be addressed in a sensitive analysis together with the case of congestion module. Similarly, a baseline scenario with zero traffic growth is used. The fuel economy is derived directly from Vision model, which provides the fuel economies for passenger cars and trucks until 2100 (US DOE, 2010). The model presents the fuel economy by a decade interval so a linear interpolation is used if fuel economy of a certain year is desired. In LCA, a fleet on-road average fuel economy is used instead of the certificate one specified by auto manufacturers.

Increasing pavement roughness causes more vibrations and reduces driving speed, and thus increases fuel consumptions and pollutant emissions of vehicles. An international roughness index (IRI, m/km) is generally used to describe the level of roughness. No theoretical or empirical models are available to predict the IRI development trends for this project, so the IRI development trends estimated from the MEPDG software are used, as depicted in Figure 2. The MEPDG software estimates the IRI trend incrementally over the pavement design period on a monthly basis, based on pavement distresses predicted using a series of pavement performance models built in the software.

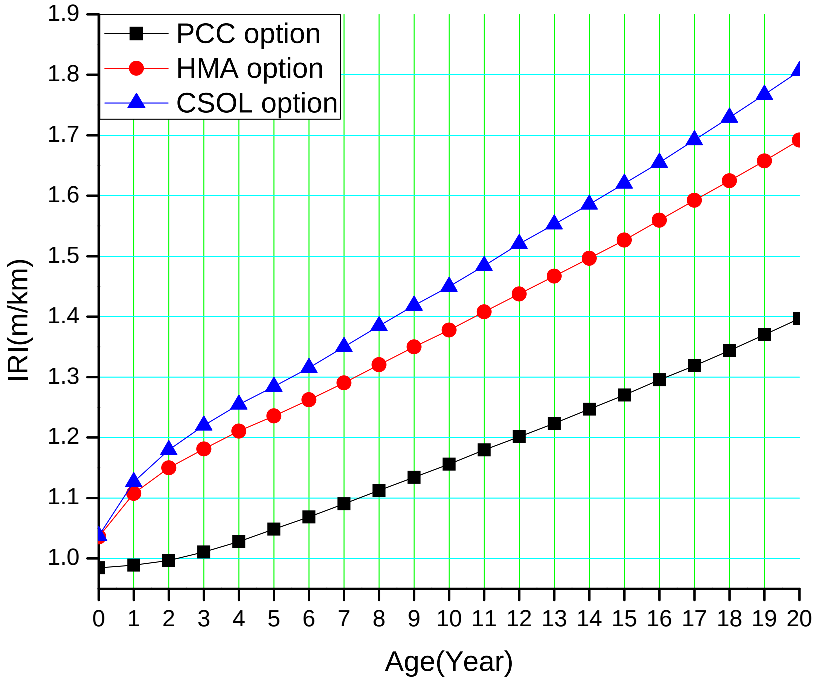

FIG.2 Development Trends of IRI for Three Scenarios

Increase of IRI reduces fuel economy, and the relationship was revealed by the findings of Missouri DOT: the fuel economy was promoted from 21.30 mpg to 21.47 mpg for gasoline powered passenger cars, and from 5.91 mpg to 6.11 mpg for diesel powered trucks as the IRI was ameliorated from 2.03 m/km to 0.95 m/km (Amos, 2006). Based on the above data, a fuel consumption factor (FCF) is used to describe the real fuel consumptions of vehicles driving on pavements with different IRI values, which is estimated by:

$$\begin{aligned} FCF &= 7.377e-3IRI+0.993 \quad \text{for passenger cars} \\ FCF &= 2.163e-2IRI+0.953 \quad \text{for trucks} \end{aligned} \tag{2}$$

It is assumed that IRI is restored to its initial values when rehabilitation activity of every 16 years is performed. The LCA inventory is calculated as the differences between driving on real pavement and on an ideally smooth pavement.

Besides the influence on fuel economy, increase of IRI reduces the driving speed and thus leads to a reduction of highway capacity. According to Chandra's research (2004), highway capacity is reduced by approximately 150 vehicles per hour per lane when IRI is increased by 1 m/km. The speed reduced fleet may witness significant fuel consumption increase and emission pollutant changes. Under the three IRI development scenarios from Figure 2, the potential highway capacity reductions are estimated accordingly, which are then reflected into the QuickZone model to estimate the possible delay and amounts of detours.

Moreover, additional roughness causes increased friction and vertical acceleration of the vehicle body, and thus leads to more vehicle fuel consumption and pollutant emissions. A typical torque curve for an engine (Tunnell and Brewster 2005) was used to estimate the emission, which defines a not-to-exceed zone. Constrained by this zone, a constant emission rate is assumed for a typical operation speed (90–105 km/h). Any additional emissions produced from engine load increase can be estimated as proportional to the fuel consumption increase calculated by Eq. 2 (Zhang et al. 2010).

3.3.2 Pavement Structure Effect

Pavement structures have significant influences on fuel consumptions of vehicles, especially for asphalt pavements as compared with PCC and composite pavements (CSOL option is treated as composite pavement in this study) (Taylor et al. 2000). The third phase of a study performed by the NRC and Cement Association of Canada (Taylor and Patten 2006) suggested that PCC and composite pavements have phenomenal fuel economy advantages over HMA pavement. Their results are summarized and transformed to be applied to Florida temperature range, as shown in Table 5. The concrete pavement is set as the baseline road type. The transformation was carried out by discarding winter season data, applying spring data to winter season, summer data to summer and fall seasons, fall data to winter season in Florida State.

TABLE 5. Fuel Economy Comparisons of Three Pavement Structures

Season	**Winter**		**Spring**		**Fall**		**Winter**	
For passenger cars								
Pavement type	HMA	CSOL	HMA	CSOL	HMA	CSOL	HMA	CSOL
Comparison (in percent)	3.1	-2.07	-0.42	1.2	-0.42	1.2	-0.42	1.2
For trucks								
Pavement type	HMA	CSOL	HMA	CSOL	HMA	CSOL	HMA	CSOL
Comparison (in percent)	0.86	2.0	1.58	0.9	1.6	-1.34	1.6	-1.34

The additional fuel consumptions are expressed as the differences between HMA, CSOL pavements and PCC pavements. And the associated air emissions are calculated following the convention of estimating the air emissions in the “IRI Effect” sub-section.

3.3.3 Albedo

Albedo directly contributes to global cooling by adjusting the radiative forcing of the earth’s surface. As a surface covering, pavements can reflect a portion of the incoming solar radiation back into space, thus adjusting the global energy balance. Akbari et al. (2008) estimated that for every square meter, 2.55 kg of emitted CO_2 is offset for every 0.01 increase in albedo due to increased radiative forcing. Equation 3 gives the means to calculate the benefit:

$$\Delta m_{co_2} = 100 \times C \times A \times \Delta\alpha \tag{3}$$

where Δm_{co_2} is the mass equivalents of CO_2 mitigated (kg); C is the CO_2 offset constant (kg CO_2/m2); A is the area of pavement (m2); $\Delta\alpha$ is the change is albedo.

The expected albedo range is 0.05 to 0.20 for a typical asphalt pavement, and 0.25 to 0.46 for a typical concrete pavement (Pomerantz et al. 1998). Aged asphalt pavements tend to have higher albedo, while the opposite is true for concrete pavements (Pomerantz and Akbari. 1997). In this LCA, the three plans are compared with the old PCC pavement with an albedo of 0.25. For PCC plan, the albedo is set to 0.35; for HMA and CSOL plans, the albedo is set to 0.15 (Pomerantz and Akbari. 1997).

3.3.4 Carbonation

Over time, much of the CO_2 that was originally liberated from limestone during cement kiln processes will rebind itself to the cement in the pavement through the carbonation process. The carbonation of concrete can be modeled using a simplification of Fick’s second law of diffusion (Lagerblad 2006):

$$d_c = k\sqrt{t} \tag{4}$$

where d_c is the depth of carbonation (mm); k is the rate factor (mm/y1/2); t is time (year).

A study by Portland Cement Association found carbonation rate factors of 8.5, 6.7, and 4.9 for concrete with compressive strengths of 21, 28, and 35 MPa, respectively (Gajda 2001). The k value used in this study is 6.3 via linear interpolation.

However, not all of the calcium in the concrete is expected to bind CO_2 molecules; the binding efficiency is suggested to be roughly 75% (Stolaroff et al. 2005). The mass of CO_2 sequestered is given by Equation 5.

$$m_{co_2} = d_c \times A \times \rho_{concrete} \times m_{cement/concrete} \times \frac{M_{co_2}}{M_{CaO}} \times \varepsilon \tag{5}$$

where m_{co_2} is the mass of CO_2 sequestered through carbonation (kg); d_c is the depth of carbonation (m); A is the surface area of pavement (m2); $\rho_{concrete}$ is the density of concrete (kg/m3); $m_{cement/concrete}$ is the mass ratio of cement in concrete; M_{co_2} is the molar mass of CO_2 (44g/mol); M_{CaO} is the molar mass of CaO; ε is the binding efficiency of CO_2 to CaO.

3.4. EOL Module

Most of the previous studies do not include this module because they deem the pavement structure with indefinite life span which can still provide service as long as rehabilitation and M&R activities are geared. For those considering EOL module, the majority simply landfill the pavement materials.

Reclaimed concrete material (RCM) can be used to substitute a small portion of coarse or fine aggregates in concrete pavements, but more frequently, as aggregates in base course. Reclaimed asphalt pavement (RAP) is now routinely accepted in asphalt paving mixtures as a portion of aggregate and binder substitute. Substitution rates range from 10 to 50 percent or more, depending on state specifications. However, asphalt mixes incorporating more than 20% RAP may suffer a reduction in quality (Federal Highway Administration [FHWA] 2008).

In this LCA, two scenarios are tested. One is to crush PCC pavement and use 10 and 20 percent of the crushed materials in base course layer. The other is to recycle the milled asphalt mixture into plant with a portion of 10 and 20 percent. RAP are treated as free of any inherent or feedstock energy, whereas, in fact, it retains its feedstock value indefinitely. Also, this study has included the energy used to extract RAP (roadway milling) and its transportation to the asphalt plant where it is remixed, but excluded other possible energy demands because milled RAP are very consistent and can be used in new mixes without further screening or crushing (FHWA, 2011).

The inclusions of recycled materials are reflected by the energy demand reduction in material module in the sensitivity analysis section

4. LIFE CYCLE INVENTORY AND IMPACT

The inventories of this LCA model over a 40-year life span are obtained from previous sections. And the environmental impacts of the inventories are indicated by energy consumption, global warming potential, and other air pollutant emissions.

4.1. Energy Consumption

As reflected in Figure 3, the total energy consumed for 1 km of PCC, HMA, and CSOL overlays are 61 TJ, 129 TJ, and 101 TJ, respectively. That is, HMA and CSOL options consume 109 and 65 percent more energy as compared with PCC option. The energy consumptions for three scenarios are all dominated by material, congestion, and usage phases. If usage phase is not considered, as many previous studies did, the energy consumptions for PCC, HMA, and CSOL options witness reductions of 40, 50, and 44 percent. Feedstock energy occupies a significant portion of the total consumed energy, and will significantly reduce the energy consumption for HMA and CSOL options if it is not counted. However, this will not influence the preferences of three options. Details of the inventory are listed in Table 6.

Three major sources contribute to the preferences of PCC option over HMA and CSOL options: first, concrete is a much less energy intensive material as compared with HMA; second, PCC pavement has a low IRI increase rate, and thus consumes less fuel; third, PCC pavement structure is beneficial to fuel savings.

4.2. Greenhouse Gas Emissions

Greenhouse gas (GHG) emission inventory in this LCA study includes CO_2, methane (CH_4), and N_2O. The global warming impact is expressed as GHG emissions in tonne of CO_2 equivalent. This is calculated by multiplying the mass of each GHG emission by its global warming potential (GWP). Specifically, GWP is 1 for CO_2, 23 for CH_4, and 296 for N_2O (Houghton 2001). Figure 4 shows the global warming impact of each overlay system.

GHG is dominated by material, congestion, and usage modules for all three pavement rehabilitation options. And the GHG emissions from the usage phase are overwhelming for HMA and CSOL, which can be explained by the following reasons: first, carbonation gives credit to PCC overlay which offsets tremendous amount of CO_2 while HMA and CSOL option cannot enjoy this benefit; second, albedo brings benefits to PCC option as compared with HMA and CSOL options since PCC overlay has a lighter color, and thus reflects more heat back to air. For the three GHGs, CO_2 dominates, sharing more than 90 percent for the three options.

TABLE 6. Inventories of Three Alternatives

Input-output		**Energy (GJ)**		**CO_2 (tonne)**	**CH_4 (kg)**	**N_2O (kg)**	**VOC (kg)**	**NO_X (kg)**	**CO (kg)**	**PM_{10} (kg)**	**SO_X (kg)**
		Primary	Feedstock								
PCC	Material	12709	NA	1219	659	4	111	2194	14118	3168	1158
	Distribution	185	NA	14	16	0.3	5	17	8	2	4
	Construction	70	NA	4	0a	negligible	23	291	133	14	8
	Congestion	11274	NA	759	0a	0a	877	-2908	-27414	116	1
	Usage	37083	NA	1863	0a	0a	3057	3376	73470	55	59
	EOL	100	NA	13	8	0.2	5	44	17	4	3
HMA	Material	13958	39034	930	2247	1	205	1994	199	64	879
	Distribution	245	NA	19	21	0.4	7	22	11	3	5
	Construction	97	NA	54	0a	negligible	30	390	172	30	11
	Congestion	10792	NA	726	0a	0a	1103	-1625	-15291	67	3
	Usage	64688	NA	4964	0a	0a	4814	5343	115670	85	92
	EOL	143	NA	37	7	0.14	22	297	168	22	8
CSOL	Material	9539	26668	636	1535	1	140	1362	136	44	60
	Distribution	118	NA	9	10		3	11	5	1	2
	Construction	74	NA	41	0a	negligible	23	312	143	24	9
	Congestion	8190	NA	551	0a	0a	1104	-1625	-15291	67	3
	Usage	56419	NA	4340	0a	0a	4767	5227	115215	86	92
	EOL	79	NA	21	4	0.1	12	165	93	12	5

NOTE: [a]0 means that the item is not within outputs of the specific models and thus a zero value is assigned. This will not influence the results significantly because CO_2 emission is three orders bigger.

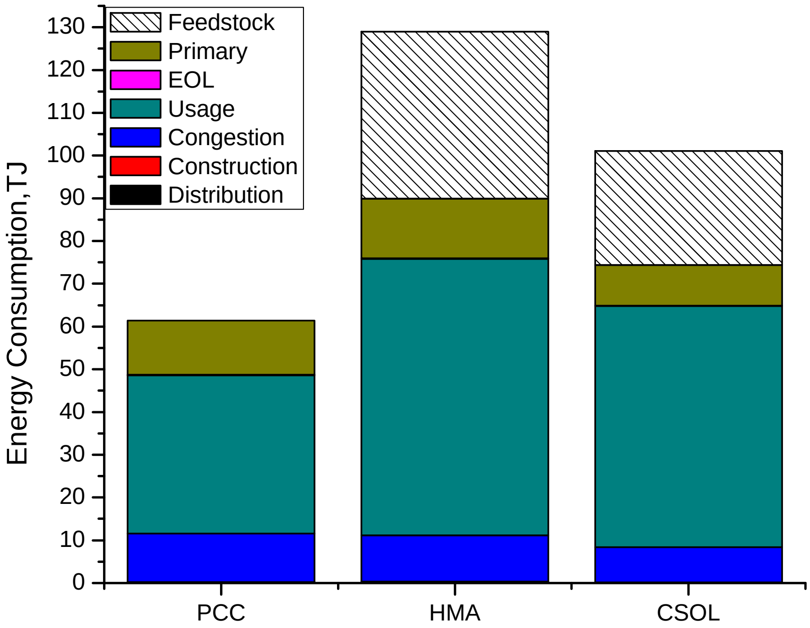

FIG.3 Total Energy Consumption by Life-Cycle Phase

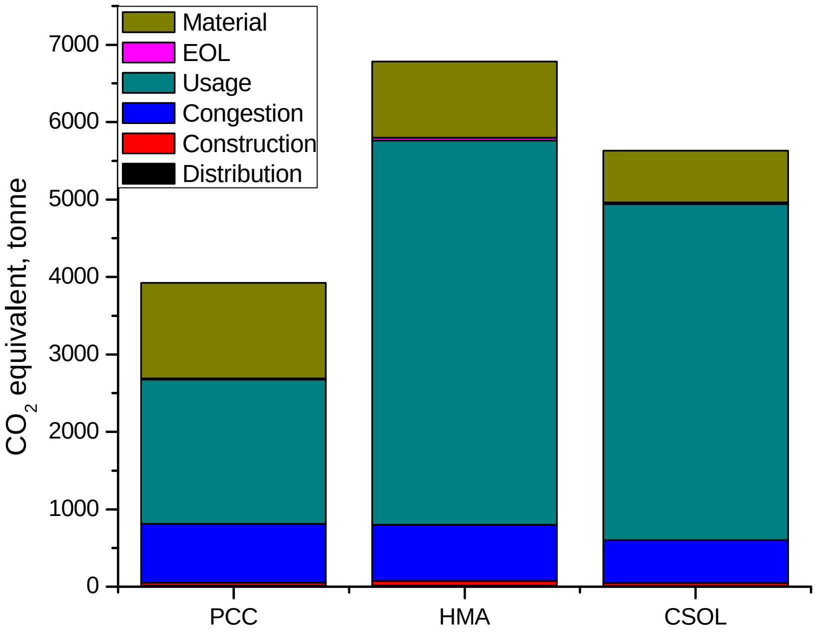

FIG.4 Greenhouse Gas Emission by Life-Cycle Phase

4.3. Air Pollutants

The air pollutant emissions other than GHG in this LCA study include: VOC, NO_X, CO, PM10, and SO_X, as depicted in Figure 5.

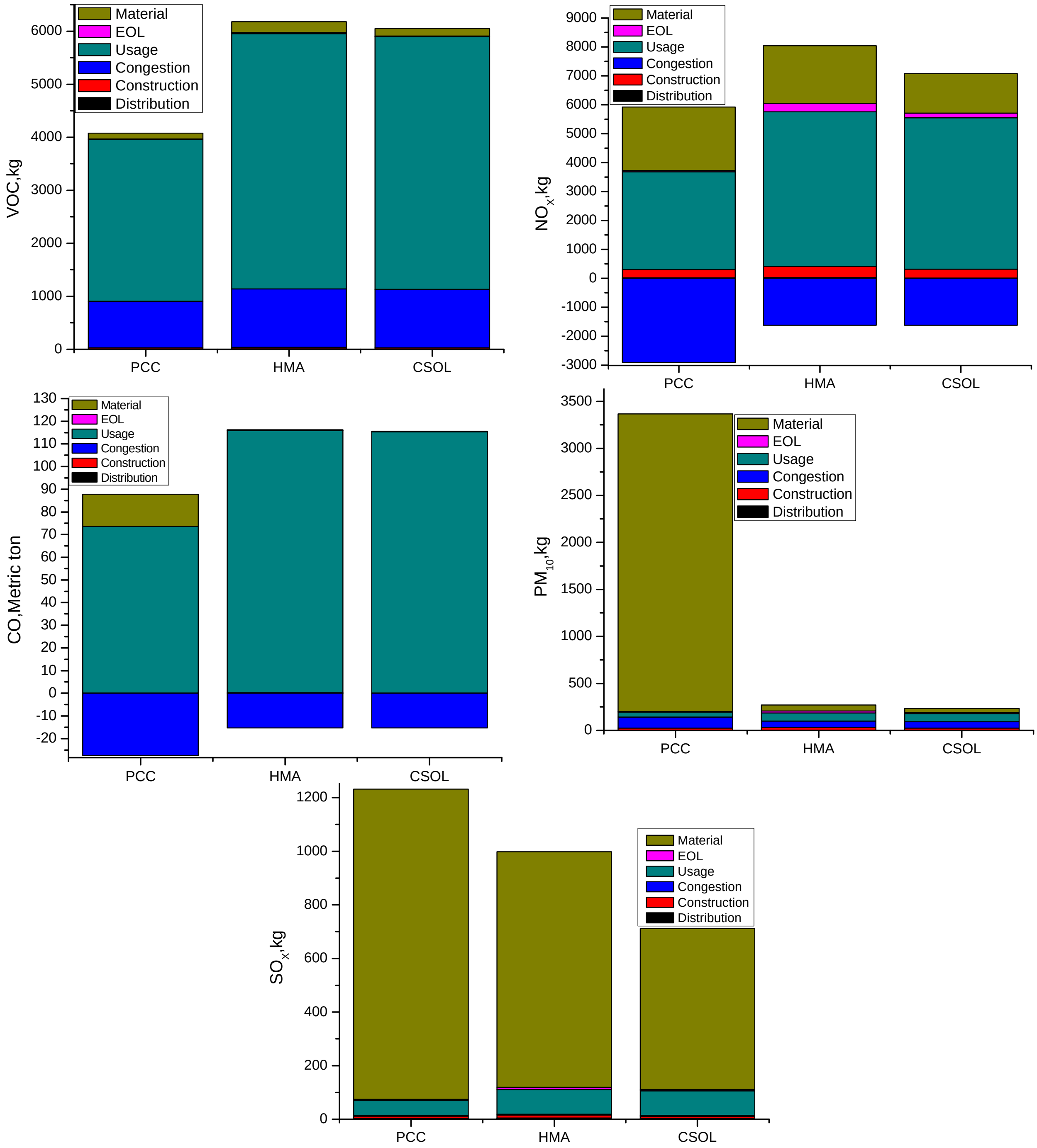

FIG.5 Air Emissions by Life-Cycle Phase

For VOC and CO, congestion and usage phases dominate the air emissions, whether in a positive or negative way. For NO_X, three sources overwhelm the other sources to contribute most, including: material, congestion, and usage modules. The emissions of NO_X and CO show negative values for congestion module. The reason for this phenomenon is the emission rates of NO_X and CO are higher at low speeds than those at high speeds while the fleet speed decreases significantly during construction periods (Sher 1998). The amount of PM10 emission from the PCC option is substantially higher than that of the HMA and CSOL options which shall be ascribed to the fact that production of cement produces tremendous amount of particle matters. For SO_X, material module shares a determining portion while usage module, unlike for other air emissions, is not the major source. New regulations requiring sulfur content in diesel fuel to be significantly reduced to 15 ppm by 2010 and to 30 ppm in gasoline by 2006 may account for this finding (EPA 2009, Gasoline Sulfur Standards, 2002).

Table 7 summarizes the life-cycle inventory results. PCC option acts as a baseline case and HMA, CSOL are evaluated by comparison with PCC.

TABLE 7. Summary of Life-Cycle Inventory and Impact Results

Item	**PCC**	**HMA (%)**	**CSOL (%)**
Energy consumption (with feedstock energy, TJ)	61.4	109	64
Energy consumption (without feedstock energy, TJ)	61.4	46	21
GHG (tonne)	3924	73	44
CO (tonne)	60	67	66
VOC (kg)	4077	52	48
PM10 (kg)	3367	-92	-93
NO_X (kg)	3014	113	81
SO_X (kg)	1232	-19	-42

4.4. SENSITIVITY ANALYSIS

This LCA study is composed of various models and employs some critical assumptions, and thus introduces significant level of uncertainties. Those assumptions, including traffic developing pattern, fuel economy improvement, surface overlay deterioration rate, and recycling percentage, may greatly influence the LCA inventory and deserve further evaluation.

The traffic growth rate in the baseline scenario is set to zero percent, while in realty traffic growth shall affect the fuel consumptions and air pollutant emissions. Several traffic scenarios, with various annual growth rates, are presented in Figure 6 to investigate their impacts. Only traffic related fuel consumption are discussed here, including the congestion module and the usage module.

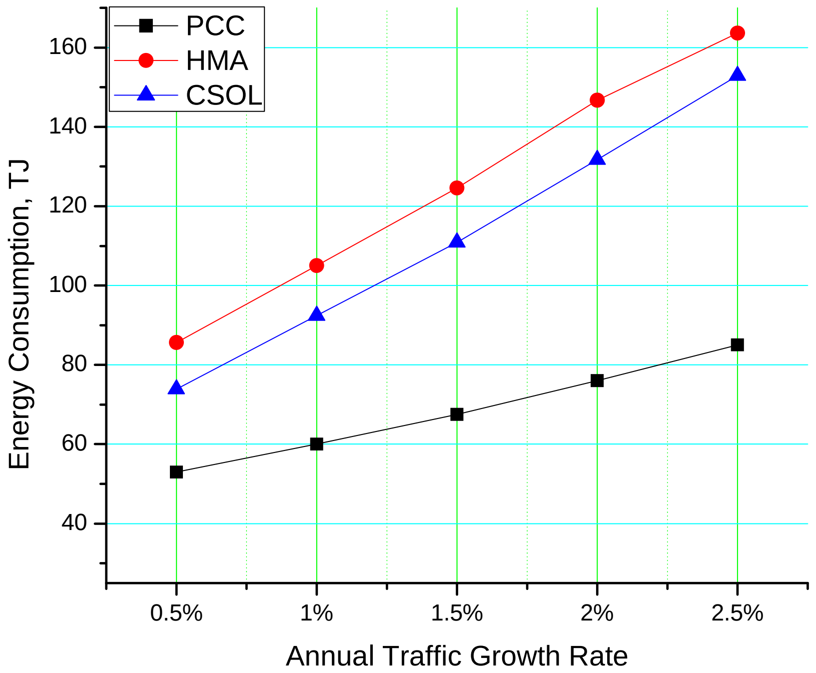

FIG.6 Sensitivity of Traffic Related Energy Consumptions due to Traffic Growth

At various annual traffic growth rates, traffic related energy consumption increases significantly, barely following a linear mode. The slopes of HMA and CSOL are much steeper than that of PCC, which suggest that the former two options are more sensitive to traffic growth, and in return, PCC option owns even more credits for a real traffic pattern. The CSOL option consumes less energy during congestion and usage phases due to a smaller intercept compared with HMA option. It needs to be addressed here that, at the 2.5 percent traffic growth rate, the queue length in congestion module at year 2042 reaches 12.0 mi, which is less likely to occur in reality. This abnormity on one hand suggests the inability of the model to account for the potential increase of highway capacity, and on the other hand hints that a road expansion may be needed. However, this does demonstrate that the energy consumption (as well as GHG emission although not presented here) is very sensitive to congestion module and could increase significantly under a high traffic growth rate scenario.

Fuel economy is also a critical factor influencing the traffic related energy consumption. The baseline scenario is set to a zero fuel economy improvement. Three alternatives, with one percent annual fuel economy improvement, hybrid technology, and two percent annual fuel economy improvement, are studied to measure the uncertainty of fuel economy parameter.

Currently, the adoption rate for hybrid technology is small (under 3 percent of new car sales in the U.S. for August 2010) (HybridCars website, 2010). And estimation of the future market share of the hybrid vehicles varies widely, from never over 10 percent of the U.S. auto market (Marketwatch website, 2010) to domination of the new car sales in the U.S. and elsewhere over the next 10 to 20 years (AllianceBernstein, 2006). A conservative estimation here is made, with an average 5 percent over the

LCA life span. A gasoline internal combustion engine (ICE) hybrid vehicle witnesses a 21.7 percent reduction of fuel consumption compared to a regular ICE vehicle (Heywood et al. 2004) when driving on a highway. Thus the hybrid technology will bring a conservative estimation of 1.4 percent fuel economy benefits in this study.

The results are plotted in Figure 7. For traffic related energy consumption, fuel economy improvement of two percent annually brings a fuel reduction of 26, 27, and 28 percent for PCC, HMA, and CSOL options, respectively.

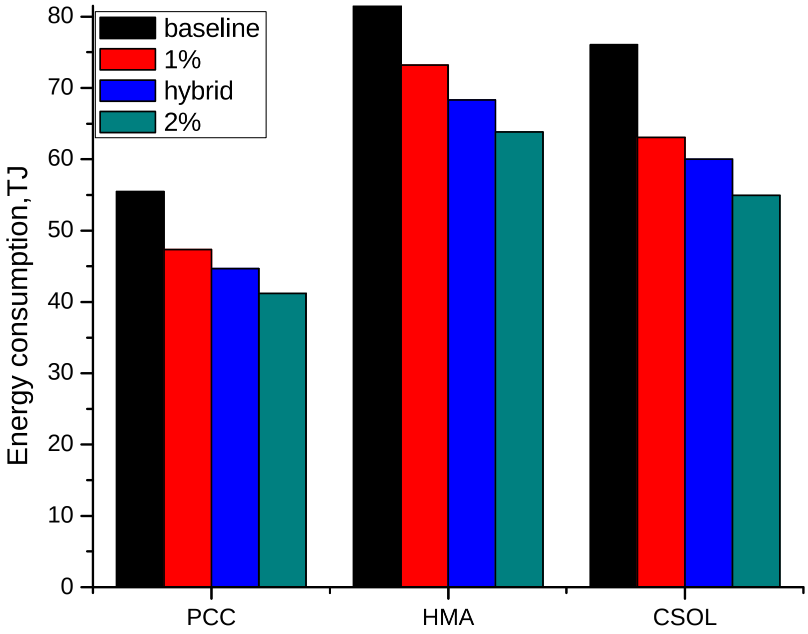

FIG.7 Energy consumption based on different fuel economy improvement scenario

IRI increase rate is another factor that would influence the traffic related energy consumption. At a two percent faster IRI developing rate (compared with the original MEPDG IRI outputs), the additional fuel consumption is 2%, 1.4%, 1.6 % for PCC, HMA, and CSOL, respectively. At a four percent faster rate, they are 4%, 2.7%, and 3.3%.

Material recycling is also investigated in the sensitivity analysis. Two scenarios, 10 percent recycling portion and 20 percent recycling portion, are studied, with results plotted in Figure 8.

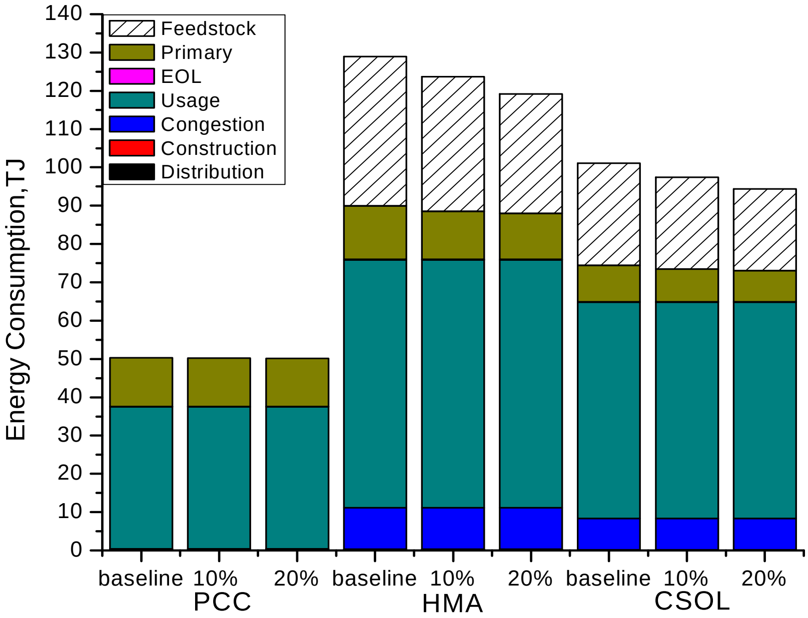

FIG.8 Benefits of Recycling Waste Materials

Recycling PCC to substitute aggregates in base course layer brings almost negligible energy consumption reduction. However, it will save plenitude of landfill space and thus bring environmental benefits. Recycling 20 percent of old HMA into new paved overlay reduces the energy demand from material modules significantly, but not enough to alter the preferences of the three alternatives.

5. CONCLUSIONS

An LCA model of pavement overlay systems, including PCC overlay, HMA overlay, and CSOL overlay, was constructed in this report. The LCA model was further divided into six modules: material module, distribution module, construction module, congestion module, usage module, and EOL module. This study spends much effort on the congestion and usage modules, and discusses the benefits of recycling waste materials, which are typically not involved or shallowly touched by most peer research. Through the study, the following conclusions are obtained:

1. The preferences of the three alternatives rank as PCC > CSOL>HMA in terms of energy consumptions and GHG emissions no matter whether the feedstock energy of asphalt is counted or not.
2. Material, congestion, and usage are three major sources of energy consumptions and air pollutant emissions, especially usage module.
3. Traffic related fuel consumption is very sensitive to traffic growth, which barely follows a linear relationship with annual traffic growth rate. PCC option demonstrates the least steep slope and smallest intercept, and thus might be the most environmental friendly option compared with the other two.
4. Traffic related fuel consumption is also very sensitive to fuel economy improvement. A two percent annual fuel economy improvement reduces the fuel consumption by 26, 27, and 28 percent for PCC, HMA, and CSOL options, respectively.
5. IRI developing rate also influences the fuel consumptions, but to a less extent as compared with traffic growth and fuel improvement.
6. Recycling materials bring negligible energy demand benefit for PCC option, but reduces the energy consumption for HMA and CSOL options significantly, although not enough to alter the preferences of the three alternatives.

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