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A FRAMEWORK FOR PAVEMENT TREATMENT ALTERNATIVE SELECTION THROUGH LIFE CYCLE COST ANALYSIS

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Abstract: Aging road infrastructure and budgetary limitations have made it increasingly important to optimize roadway maintenance, repair, and rehabilitation (MRR) expenditures in the United States. For the past few decades, several non-traditional rehabilitation techniques, such as the use of warm mix asphalt, cold in-place recycling, full depth reclamation, and intelligent compaction, have proved effective in addressing asphalt pavement deficiencies while reducing project costs, shortening activity durations, and improving quality of work. While many studies have been conducted on the life cycle costs of MRR projects, very few have evaluated non-traditional techniques with in-depth analysis of user costs. This study focuses on life cycle cost analysis (LCCA) of these non-traditional techniques by investigating agency costs, user cost due to travel delay, user cost due to additional fuel consumption, and user cost due to higher numbers of crashes. A total of six life cycle MRR alternatives were developed, where four represent the non-traditional techniques and the other two represent traditional techniques as benchmarks. Cost data for agency costs were obtained through a survey of state departments of transportation and RSMeans 2016. User cost data were obtained from literature, within which fuel consumption costs were estimated through Motor Vehicle Emission Simulator. Results show that alternatives involving asphalt recycling and intelligent compaction have lower overall life cycle costs. It is also concluded that user travel delay costs account for a major portion of the overall life cycle costs, so decision makers are recommended to select MRR techniques with minimum disruption to commuters' mobility.

1 INTRODUCTION

With limited funding and an increasing backlog of roadway rehabilitation requirements, transportation agencies in the United States need to plan and execute maintenance, repair, and rehabilitation (MRR) works while minimizing costs. Meanwhile, construction activities typically cause traffic disruptions and safety implications to road users and construction workers, as well as negative impacts on local communities. These socio-economic issues can also be aggravated by project delays. Therefore, having a clear vision of all types of costs incurred by MRR activities, both from agency perspective and user perspective, is highly important for decision-making at the project level.

An asphalt roadway pavement section typically experiences cycles of MRR activities before it is eventually reconstructed. If all MRR activities are being performed at proper intervals and there are no structural deficiencies in subbase and subgrade layers, asphalt pavement sections can have service lives up to several decades. As a result, decision makers also need to investigate the overall costs throughout the entire life cycle of pavement sections in addition to the costs of a single MRR activity.

Over the past few decades, several innovations have taken place in MRR techniques of asphalt roadways, such as the use of warm mix asphalt (WMA), cold in-place recycling (CIR), full depth reclamation (FDR), and intelligent compaction (IC). These non-traditional techniques have proved effective or shown potential in reducing agency cost, shortening schedule, and/or improving quality. However, it remains to be seen what implications these non-traditional techniques provide from a life cycle cost perspective from both agency and user perspectives.

Consequently, this research focuses on developing a framework to determine the life cycle agency and user costs of MRR projects involving these non-traditional techniques and investigating the potential life cycle cost savings they provide when compared to traditional alternatives. Agency cost data are collected through a survey of state departments of transportations (DOTs) with supplementary data collected from RSMeans. User costs are calculated through simulations using Motor Vehicle Emission Simulator (MOVES) along with published cost data from the literature.

It is concluded that user costs resulted from travel delay, additional fuel consumption, and safety issues account for a major portion of the overall life cycle costs, and MRR techniques involving asphalt recycling generally have lower overall life cycle costs, both of which coincide with existing literature. Using the proposed framework, public agencies are encouraged to investigate potential trade-offs between agency and user costs should conflicts arise between the two, and ultimately make informed decision on choosing the appropriate MRR alternatives at a project level.

2 BACKGROUND

2.1 Life Cycle Cost Analysis

Life cycle cost analysis (LCCA) is an evaluation tool used to assess project costs and support investment decision-making. It allows a direct and comprehensive comparison of alternatives by including all relevant costs that occur throughout the entire life cycle (i.e., both direct costs to the agency and the effects of MRR activities on users) (FHWA 2012).

Although a typical LCCA covers all phases of roadways, some existing studies involving LCCA have focused on the maintenance and rehabilitation phases (Harvey et al. 2012; Pittenger et al. 2012; Pour and Jeong 2012; Lee et al. 2011; Pittenger et al. 2011; Chen and Flintsch 2007; Bemanian et al. 2006). However, to the authors' knowledge, there is no research that has evaluated non-traditional MRR techniques and, at the same time, analyzed both agency and user life cycle costs. This study aims to fill this gap and demonstrate the economic performance of non-traditional techniques through LCCA.

2.2 MRR Techniques for Asphalt Roadways

In the United States, asphalt roadway maintenance, repair, and rehabilitation works are traditionally performed through crack seal (using bituminous sealants to fill cracks on pavement surfaces), chip seal (placing mixture of asphalt aggregates and binder on existing pavement to address surface distresses), patching (removing localized distressed pavements areas and applying new asphalt mixture), milling and overlay (replacing the surface course of deteriorated pavement sections with a new asphalt layer), and plant or in-place recycling (Wang et al. 2011). Meanwhile, over the past few decades, a good number of alternatives have been developed in order to reduce costs, accelerate construction, reduce raw materials used, and/or improve quality. A summary of characteristics and features of several non-traditional MRR techniques for asphalt pavement sections from existing literature (Bonaquist 2011; West et al. 2014; Anderson et al. 2008; Gao et al. 2014; Lane and Lee 2014; Swiertz 2015; Bocci et al. 2012; Mooney et al. 2010; Savan et al. 2015) is shown in Table 1.

Table 1: Characteristics of Non-Traditional Roadway MRR Techniques

MRR Technique	Description	Documented Benefits
Warm mix asphalt (WMA)	Asphalt mixtures that are produced at lower temperatures (by 50°F or more) than those typically used in the hot mix asphalt (HMA) production through asphalt foaming or by using additives	Reduced fuel use, reduced plant emissions, improved working conditions, better workability for compaction, extended paving season, higher portions of allowable reclaimed asphalt pavement
Cold in-place recycling (CIR)	The existing pavement materials are reused in-place without using heat, through applications of recycling agents (e.g. lime, fly ash, cement, and lime kiln dust).	Shorter construction schedules, reduced need for virgin materials, reduced fuel consumption and emissions, and potential re-application once the pavement reaches end of service life
Full depth reclamation (FDR)	The entire pavement layers and a portion of the base or subbase layer are uniformly pulverized, mixed, and stabilized to form the binder and base course	Reduced future maintenance needs as lower layer deficiencies are resolved, reduced need for producing and transporting virgin materials, and reduced fuel consumption and emissions
Intelligent compaction (IC)	Paving process is monitored and controlled in real-time by instrumentations (infrared sensors, accelerometers, GPS, etc.) to improve compaction	Optimized labor utilization, shortened construction time, reduced fuel consumption, and minimized equipment wear-and-tear. Improved compaction quality

2.3 Survey of US State Departments of Transportation

In order to investigate the current practices with regards to both traditional and non-traditional MRR techniques, a survey of state departments of transportation (DOTs) has been conducted by the authors (Salman et al. 2017). The survey results have revealed the popularity, amount of work, average unit costs, construction time, and expected service life extensions of various non-traditional MRR techniques. These information have provided data for the life cycle cost analysis in this study.

3 METHODOLOGY

3.1 Data

For agency costs, to the authors' knowledge and observation from the survey results, the costs of MRR activities vary greatly across different public agencies across the US. Therefore, for demonstration purpose, cost values for relevant MRR activities in this research are selected, calculated, or adjusted to reflect national averages, as shown in Table 2. Specifically, activities and their specifications are obtained from Athena Sustainable Materials Institute; estimated service life values are derived from the survey and existing literature; activity durations are calculated using productivity rates from RSMeans 2016; average costs for MWF, CIR, and FDR are derived from survey results after adjusting for locality according to RSMeans 2016, with the rest average costs obtained directly from RSMeans 2016.

For user costs, data needed to calculate value of time are collected from US Department of Transportation (USDOT), New York State Department of Transportation (NYSDOT), and Data USA; data needed to calculate user costs because of additional fuel consumption are obtained from US Energy Information Administration (USEIA); and data needed to calculate user costs because of increased number of crashes are collected from NYSDOT and National Highway Traffic Safety Administration (NHTSA).

Table 2: Summary of Asphalt Roadway MRR Activities

Activities	Specifications	Estimated Service Life (Years)	Duration per lane (Days)	Average Cost per lane (1K USD)
Crack Seal (CS)	(a): 1000ft / ln	3	1	2.2
	(b): 1500ft / ln	3	1	3.3
	(c): 3750ft / ln	4	3	8.3
	(d): 4500ft / ln	4	3	10.0
Patch	(a): 2% lane area	8	3	13.8
	(b): 3% lane area	8	5	21.1
Mill & HMA Fill (MHF)	(a): 2", no shoulder	9	15	136.6
	(b): 4" with shoulders	15	37	358.5
Mill & WMA Fill (MWF)	(a): 2" no shoulder	9	15	130.4
	(b): 4" with shoulders	15	37	341.0
HIPR	Recycle 4" + 2" HMA	15	16	268.8
CIR	Recycle 4"+ 2" HMA	15	16	271.2
FDR	Recycle 6" + 2" HMA	18	21	369.5
Mill & HMA Fill with IC (MHFIC)	(a): 2" no shoulder	10	15	140.7
	(b): 4"with shoulders	17	37	369.2

3.2 MRR Alternatives

Using the information and data from Table 2, a total of six (6) alternatives are developed with four (4), labeled as “WMA”, “CIR”, “FDR”, and “IC”, representing respective non-traditional techniques, while the other two (2), labeled as “Traditional” and “HIPR”, represent traditional techniques as benchmarks. The subject asphalt roadway section is a one-mile long single-bound two-lane Interstate highway in Onondaga County, NY. The section has a lane width of 12 feet with paved shoulders on both sides, and it consists of the following layers: (i) a surface course of 2” thickness (ii) a binder course of 2” thickness (iii) a base course of 6” thickness, and (iv) a granular subbase course of 12” thickness. An Interstate section is selected considering that Interstates play a critical role in ground transportation and that Interstate MRR activities are labor- and material-intensive.

A life cycle of 35 years is selected for this study based on the recommendation from Federal Highway Administration (FHWA). Each alternative has a number of MRR activities taking place at different years throughout the 35-year analysis period. These activities combined form a rehabilitation schedule for each alternative, as shown in Table 3. The major differences across the six alternatives are the timing of certain MRR activities and the rehabilitation techniques adopted. For the execution of MRR activities, a lane closure is used where one of the two lanes of the subject roadway section is closed and the other lane is left open to traffic.

Table 3: Rehabilitation Schedules for MRR Alternatives

Traditional		**HIPR**		**WMA**		**CIR**		**FDR**		**IC**	
Y*	**Activity**	**Y**	**Activity**	**Y**	**Activity**	**Y**	**Activity**	**Y**	**Activity**	**Y**	**Activity**
0	MHF(b)	0	HIPR	0	MWF(b)	0	CIR	0	FDR	0	MHFIC(b)
3	CS(a)	3	CS(a)	3	CS(a)	3	CS(a)	5	CS(a)	4	CS(a)
7	CS(c)	7	CS(c)	7	CS(c)	7	CS(c)	9	CS(c)	8	CS(c)
10	Patch(a)	10	Patch(a)	10	Patch(a)	10	Patch(a)	12	Patch(a)	11	Patch(a)
15	MHF(a)	15	MHF(a)	15	MWF(a)	15	MHF(a)	18	MHF(a)	17	MHFIC(a)
21	Patch(b)	21	Patch(b)	21	Patch(b)	21	Patch(b)	24	Patch(b)	23	Patch(b)
24	MHF(b)	24	HIPR	24	MWF(b)	24	CIR	27	FDR	27	MHFIC(b)
27	CS(b)	27	CS(b)	27	CS(b)	27	CS(b)	32	CS(b)	31	CS(b)
31	CS(d)	31	CS(d)	31	CS(d)	31	CS(d)			35	CS(d)
34	Patch(a)	34	Patch(a)	34	Patch(a)	34	Patch(a)				

3.3 Life Cycle Cost Items

Cost items included in a typical project-level life cycle cost analysis can be categorized into agency costs and user costs. Agency costs usually refer to the costs of MRR projects, while user costs may include costs of travel delay, additional fuel consumptions and emissions, vehicle operations and repairs, crashes, and disturbance to the local community (e.g. noise).

In this study, user costs vehicle operations and repairs is negligible because the existence of work zones does not change the distance traveled. It is also assumed that the roadway section is not located in a heavily populated area, so the disturbance to adjacent residents and the adverse impacts of emissions on the local community is minimum. Therefore, the life cycle user cost items included in this research are user travel delay costs, user additional fuel consumption costs, and user increased crash costs.

3.3.1 Agency Life Cycle Costs

Agency life cycle costs of all six alternatives are derived from the cost data in Table 2 and the numbers of years values in Table 3. Present values of all six alternatives are calculated with a discount rate of 4%. It is assumed that the costs associated with performing these MRR activities remain constant for the entire analysis period. The salvage value at the end-of-life of the roadway section is not taken into consideration due to the subjective nature of assigning an arbitrary salvage value and due to the negligible contribution of salvage values at the end of a 35 year time period. The initial construction cost of the currently existing highway section is also excluded from the analysis.

3.3.2 User Life Cycle Costs – Travel Delay

User travel delay costs are determined by (1) travel time delay per vehicle, (2) traffic volume, and (3) the monetary value of time. During the execution of MRR activities, because of the lane closure, vehicles in the upstream direction approaching the work zone would have to slow and merge to the open lane, which may result in congestion. After vehicles travel through the work zone at a lower speed, they would accelerate to the regular speed once both lanes become available at the downstream. These behaviors would result in travel time delay compared to the regular traffic scenario where there is no work zone.

To estimate the travel time delay per vehicle, the combined travel time through the three links (upstream, work zone, and downstream) is compared to the travel time through the same total length of roadway section at a regular speed. The average vehicle speeds in upstream link are heavily affected by traffic volumes. Therefore, following USEPA recommendations (Carlson and Austin 1997), average speed values in the upstream link are selected based on the level of service (LOS), while average speed values in the work zone and downstream links are assumed to be constant. Using these average speed values under each LOS, the travel time delay per vehicle can be calculated in seconds, as shown in Table 4.

Table 4: Average Speeds in mph and Travel Time Delays for MRR Scenarios

Link	**Distance**	**Regular Scenario**	**MRR Scenario**			
			LOS A-C	**LOS D**	**LOS E**	**LOS F**
Upstream	0.5 mile	63	60	53	30	19
Work Zone	1 mile	63	45	45	45	45
Downstream	0.5 mile	63	60	60	60	60
Travel Time (s)						
Upstream	0.5 mile	28.57	30	33.96	60	94.74
MRR	1 mile	57.14	80	80	80	80
Downstream	0.5 mile	28.57	30	30	30	30
Total	2 miles	114.29	140	143.96	170	204.74
Travel Time Delay (s)			25.71	29.68	55.71	90.45

Assuming an annual average daily traffic (AADT) of 30,000, the hourly traffic volumes can be calculated based on the hourly distribution of daily traffic from Motor Vehicle Emission Simulators (MOVES) software default values for Onondaga County, New York. Using the hourly traffic volumes, the hourly LOSs can be calculated based on average vehicle spacing. As a result, the daily traffic volumes under each LOS can be determined as shown in Table 5.

Table 5: Daily Traffic Volumes under Each Level of Service (LOS)

Level of Service (LOS)		A	B	C	D	E	F
Regular	Weekday	5,170	17,402	9,447	0	0	0
	Weekend	7,374	17,577	0	0	0	0
MRR	Weekday	1,052	1,166	1,818	4,028	12,516	11,441
	Weekend	1,250	2,278	3,730	3,910	13,784	0

According to USDOT's guidelines on the monetary value of passenger car travel time, local personal travels, intercity travels, and business travels are valued at 50%, 70%, and 100% of hourly income, respectively (USDOT 2011). Additionally, 25% of personal trips are for work and work-related purposes (USDOT 2013). Based on these guidelines and the hourly traffic distribution at Onondaga County, New York (70% of personal travels are local travels and the remaining 30% are intercity travels), the overall value of time for passenger cars is 67% of hourly income. The monetary value of truck travel time is 100% of hourly income. The average vehicle occupancy by NYSDOT is 1.67 for passenger cars and 1.057 for trucks (NYSDOT 2013). The 2016 median household income for Onondaga County, NY, is $57,365 (Data USA n.d.). Therefore, based on a truck percentage of 13%, the value of time is calculated as $30.64 per vehicle-hour. With travel time delay per vehicle, traffic volume, and value of time determined, the costs of travel delay are calculated.

3.3.3 User Life Cycle Costs – Additional Fuel Consumption

MOVES is used to simulate the vehicle operations for all three links in Figure 1 and estimate vehicle fuel consumption levels. The inputs required by MOVES include traffic volume, hourly traffic distribution, traffic composition, vehicle age distribution, link distances, link speeds, and operation mode distributions. Using the speed values in Table 4, the operation mode distributions are determined according to suggestions by Qi et al. (2016). The MOVES results of additional fuel consumption per vehicle under each LOS are summarized in Table 6. Combining with daily traffic volumes shown in Table 5, additional daily fuel consumption values can be calculated by comparing MRR scenarios against the regular scenario.

Table 6: Additional Fuel Consumption per Vehicle under Each Level of Service (LOS)

Level of Service (LOS)		A-C	D	E	F
Additional Fuel Consumption per Vehicle (MJ)	Passenger Car	0.180	0.218	0.438	0.898
	Truck	0.240	0.292	0.562	0.758

The energy density values for gasoline (for passenger cars) and diesel (for trucks) are calculated as 137.16 MJ/Gallon and 144.54 MJ/Gallon, respectively. The fuel costs in Onondaga County as of August 2016 were $2.219/Gallon and $2.406/Gallon for gasoline and diesel, respectively (USEIA n.d.). Therefore, the daily costs of additional fuel consumption are calculated as $283 for weekdays and $138 for weekends. The unit costs of fuels are assumed to be constant throughout the analysis period due to the complexity of predicting future fuel prices.

3.3.4 User Life Cycle Costs – Increased Number of Crashes

Existing literature has established relationships between crash rates and volume capacity ratios (v/c ratios) (Zhou and Sisiopiku 1997). Since a work zone is created during MRR projects, v/c ratio in the upstream link is expected to change dramatically, which will potentially result in an increased number of crashes. The change in the number of crashes in the MRR and downstream links is ignored. The determination of lane capacity follows corresponding guidelines in Highway Capacity Manual (2010). Then, based on the hourly v/c ratios under MRR and regular traffic scenarios, the changes in hourly crash rates, measured by 100 million vehicle miles traveled (100 MVMT), are calculated. Finally, the numbers of daily additional crashes, for weekdays and weekends, can be obtained. Table 7 shows the equations for crash rates and v/c ratios and the results of daily additional crashes.

Table 7: Equations between crash rates and volume capacity ratios and Daily Additional Crashes

	Equation	Additional Crashes per 100 MVMT
Weekday	$488\,(v/c)^2 - 494\,(v/c) + 248$	2748073
Weekend	$592\,(v/c)^2 - 755\,(v/c) + 312$	-731364

It is worth noting that on weekends, the number of additional crashes is negative, indicating an improvement in traffic safety because of MRR activities. This is because according to the two equations, very low or very high v/c ratios contribute to high crash rates, while v/c ratios between 0.5 and 0.7 lead to the least numbers of crashes. Very low v/c ratios would most likely represent night and early morning traffic conditions, where poor visibility, excessive speeding, driver fatigue, and higher rates of driving while intoxicated may cause higher crash rates. Very high v/c ratios, on the other hand, indicate congested conditions that make multi-vehicle crashes more likely and frequent (Zhou and Sisiopiku 1997). In the MRR scenario, weekend hourly v/c ratios are closer to the "safest" values compared to those in the regular traffic scenario. This results in a negative number of additional crashes.

The cost of each vehicle crash varies greatly depending on the locality, severity, and boundaries of impacts being considered. According to NYSDOT, the direct economic costs of one crash event are summarized in Table 8 (NYSDOT 2015). It is also concluded that societal harm from vehicle crashes due to loss of quality-of-life accounts for 71% of the overall impacts, with the remaining 29% corresponding to the direct economic costs (Blincoe et al. 2010). These observations form the basis on which the costs of crashes are determined, and a weighted average of $119,252 is calculated as the overall cost for each crash including both the direct economic cost and the social cost due to loss of quality-of-life.

Table 8: Direct economic cost per crash and fractions of types of crashes

	Fatal	Injury	Property Damage Only
Cost in 2015 USD	$3,355,700	$90,100	$3,800
Probability	0.31%	23.63%	76.06%

With the daily agency and user costs (including costs of travel delay, costs of additional fuel consumption, and costs of higher number of crashes) determined, the MRR activity costs can be calculated by combining the daily cost with activity durations (Table 2). Then, life cycle costs can be obtained by converting these future MRR activity costs to their present worth equivalents based on the MRR schedule (Table 3) using a selected discount rate (4%). A sensitivity analysis is also performed using a range of discount rates (from 3% to 7%).

4 RESULTS

The life cycle costs under each cost item and the overall life cycle costs for all six alternatives are summarized in Table 9 in 2016 US dollars for Onondaga County, New York, with a 4% discount rate. Table 10 shows the results of a sensitivity analysis of the overall life cycle costs using 3% to 7% discount rates.

Different cost data or conditions may be applied to this LCCA framework to generate different results as a "what-if" scenario analysis. For example, based on the "Traditional" alternative, this framework can be used to explore the favourability of accelerated construction by working overtime to reduce the project duration. The potentially increased agency costs of accelerated construction can be estimated using relevant data regarding overtime rates from RSMeans, while the user costs may be lowered due to shorter MRR activity schedules. Depending on the rates and activity duration reductions, one may determine whether or not there are overall life cycle costs savings by applying accelerated construction.

Table 11 summarizes the results of a “what-if” scenario analysis of accelerated construction assuming that the milling crew works two additional hours on weekdays and are paid twice as much for overtime hours. Under these conditions, this LCCA framework shows that accelerated construction through overtime results in an overall life cycle cost saving, indicating a potentially more desirable strategy compared to regular work schedule.

Table 9: Life cycle costs for alternatives with a 4% discount rate

Alternatives	Life Cycle Costs in 1000 USD, Onondaga NY, 4% discount rate				
	Agency	User - Travel	User - Fuel	User - Safety	Total
Traditional	1197	2698	45	418	4357
HIPR	952	1380	23	232	2587
WMA	1142	2698	45	418	4303
CIR	958	1380	23	232	2593
FDR	1161	1426	24	228	2839
IC	1176	2566	43	396	4181

Table 10: Overall life cycle costs for alternatives with varying discount rates

Life Cycle Costs in 1000 USD, Onondaga NY					
Discount Rates	3%	4%	5%	6%	7%
Traditional	4764	4357	4031	3767	3553
HIPR	2864	2587	2362	2179	2028
WMA	4705	4303	3980	3719	3508
CIR	2871	2593	2368	2184	2034
FDR	3136	2839	2603	2414	2263
IC	4586	4181	3862	3609	3408

Table 11: Life cycle costs for normal and accelerated construction

Strategy	Life Cycle Costs in 1000 USD, Onondaga NY, 4% discount rate				
	Agency	User - Travel	User - Fuel	User - Safety	Total
Normal	1197	2698	45	418	4357
Accelerated	1256	2425	41	379	4100
Cost Savings	-59	273	4	39	257

5 DISCUSSIONS

It is observed that alternatives involving asphalt recycling (HIPR, CIR, and FDR) have lower overall life cycle costs because of both lower agency life cycle costs and lower user life cycle costs, resulting from lower quantities of virgin materials used and accelerated construction processes, respectively. The use of intelligent compaction also results in lower overall life cycle cost, making it an economically favorable strategy to incorporate IC into traditional milling and overlay technique.

Among all life cycle cost items, agency costs account for 27% to 41% of overall life cycle costs across different alternatives, with the rest 59% to 73% being user costs. Therefore, taking user costs into consideration during decision making processes is critical. Additionally, the costs of travel delay dominate the overall user life cycle costs, while cost of additional fuel consumption represents a very small fraction. This is partially because in this study lane closure is used in managing traffic during MRR projects, and the distance that vehicles travel are the same with the regular traffic scenario. The additional fuel consumption cost would be greater if vehicles were directed to detours that would result in larger travel times than traveling through the existing roadway section.

The analysis procedures presented in this study have some limitations. First, as part of the cost data stem from the survey of state DOTs, the accuracy of LCCA depends on the sample size and the quality of responses. Therefore, the results are deterministic and may not be a just reflection of the typical performance of these non-traditional techniques at a national level. Second, the “IC” alternative considers extended estimated service lives as the only benefit for intelligent compaction application because of a lack of supporting data for other benefits. Since IC application is new to many public agencies in the US, the anticipated paving duration reduction has currently been offset by the learning process of the proper use of IC instruments (Bledsoe 2015). However, as the proficiency of IC application increase, the life cycle costs of IC alternative may be updated by incorporating shorter activity durations.

6 CONCLUSIONS

Based on the analysis of the six alternatives, techniques involving asphalt recycling generally have lower overall life cycle costs than techniques that require large quantities of virgin materials to be used. The application of intelligent compaction reduces the overall life cycle costs because of increased estimated service life extension. User travel delay costs account for a major portion of overall life cycle costs, so it is highly important to consider MRR techniques that have the least adverse impacts on commuters’ mobility. Should conflicts arise between agency costs and user costs, what-if scenario analysis may be performed using this LCCA framework to investigate potential trade-offs and to determine the alternative with the least overall life cycle cost.

Future studies may focus on improving alternatives according to industry practices, introducing additional life cycle cost items such as costs of disturbance to local community, and applying probabilistic cost data to generate results that reflect risk.

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