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A PROJECT-LEVEL INFRASTRUCTURE MANAGEMENT FRAMEWORK FOR SUSTAINABLE ROADWAYS

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ABSTRACT

Over the past two decades, roadway infrastructure in the United States has experienced severe deterioration, costing road users billions of dollars in wasted fuels, lost time, and higher numbers of accidents. Transportation infrastructure asset management initiatives, which aim at providing and maintaining physical infrastructure assets at an acceptable level, need to address various economic, social, and environmental issues. Therefore, the American Association of State Highway and Transportation Officials (AASHTO) has encouraged public agencies to incorporate sustainable development principles into their decision-making and organizational operations at a program level.

Meanwhile, at a project level, maintenance, repair, and rehabilitation (MRR) projects for roadway infrastructure are still mostly undertaken by traditional techniques, resulting in higher overall life cycle impacts. The use of non-traditional techniques including accelerated methods is expected to reduce the overall impacts; however there is a lack of infrastructure management frameworks that support public agencies' decision-making procedures in justifying the use of non-traditional techniques.

Therefore, the goal of this research is to develop a project-level infrastructure management framework to consider multiple factors in decision-making and to analyze the life cycle economic, social, and environmental impacts of traditional and non-traditional (including accelerated methods) roadway MRR techniques.

The proposed framework utilizes decision flowcharts and multi-criteria decision-making (MCDM) methods to shortlist alternatives that meet project requirements to facilitate preliminary decision-making. And then, this framework applies life cycle assessment (LCA) and life cycle

cost analysis (LCCA) to quantify the life cycle impacts of candidate project alternatives following the triple bottom line of sustainability. MRR techniques analyzed by the framework include hot mix asphalt (HMA) and warm mix asphalt (WMA) overlay, hot-in-place recycling (HIPR), cold-in-place recycling (CIR), full depth reclamation (FDR), intelligent compaction (IC), and use of precast concrete pavement systems (PCPS).

The decision flowcharts and MCDM model in the proposed framework are developed based on existing literature and the results of a survey of state departments of transportation in the United States. Analytical hierarchy process (AHP) and analytical network process (ANP) are used to determine the weights of criteria for the MCDM model, and a customizable decision support tool is created in a spreadsheet program to facilitate application of the model.

For the LCA-LCCA model, the overall life cycle impacts include: i) agency costs and environmental impacts, ii) user costs and environmental impacts due to lost time and wasted fuel, and iii) user costs due to increased crash events. Software programs and databases including Athena Pavement LCA, GREET®, MOVES, and other miscellaneous data sources are used for LCA; while survey results, RSMeans 2016, and other miscellaneous cost sources are used for LCCA. The LCA-LCCA model is also capable of performing what-if analysis by adjusting variables. Thus, the model allows public agencies to apply their own data and priorities based on their sustainability goals, objectives, and performance measures to obtain relevant results.

The proposed framework is illustrated through case studies and validated by expert opinion and literature contrasts. Future studies may expand this framework to include more factors in the MCDM model and additional impact items in the LCA-LCCA model.

A PROJECT-LEVEL INFRASTRUCTURE MANAGEMENT FRAMEWORK FOR SUSTAINABLE ROADWAYS

by

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LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ACEC-IL	American Council of Engineering Companies of Illinois
AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
BEES	Building for Environmental and Economic Sustainability
BFFS	Base Free Flow Speed
CIR	Cold In-Place Recycling
DBR	Dowel Bar Retrofit
DOT	Department of Transportation
EIO	Economic Input-Output
ELECTRE	ELimination Et Choix Traduisant la REalité
EPA	Environmental Protection Agency
FDR	Full Depth Reclamation
FFS	Free Flow Speed
FHWA	Federal Highway Administration
GHG	Greenhouse Gas
GIS	Geographic Information System
GreenLITES	Green Leadership In Transportation Environmental Sustainability
GREET®	Greenhouse gases, Regulated Emissions and Energy in Transportation
HIPR	Hot-in-Place Recycling
HMA	Hot Mix Asphalt
IAM	Infrastructure Asset Management
IAMS	Infrastructure Asset Management System
IC	Intelligent Compaction
IRTBA	Illinois Road and Transportation Builders Association

LCA	Life-cycle Assessment
LCCA	Life-cycle Cost Analysis
LLNL	Lawrence Livermore National Laboratory
LOS	Level of Service
MCDM	Multi-Criteria Decision-making
MOVES	Motor Vehicle Emission Simulator
MRR	Maintenance, Repair, and Rehabilitation
MVMT	Million Vehicle Mile Traveled
NCHRP	National Cooperative Highway Research Program
NIST	National Institute of Standards and Technology
NYSDOT	New York State Department of Transportation
PaLATE	The Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
PCP	Precast Concrete Pavement
PDO	Property Damage Only
PHF	Peak Hour Factor
PMS	Pavement Management System
TAM	Transportation Asset Management
TAMP	Transportation Asset Management Plan
TOPSIS	Technique for Order Performance by Similarity to Ideal Solution
UTRC	University Transportation Research Center
WMA	Warm Mix Asphalt

1 INTRODUCTION

1.1 Background Information

1.1.1 U.S. Infrastructure

The American Society of Civil Engineers (ASCE) periodically issues infrastructure report cards that reflect the well-being of U.S. infrastructure of all kinds, and the latest issue in 2017 rated the overall infrastructure condition as D+. As with specific types of infrastructure, shown in Table 1, bridges, wastewater, and rails have witnessed a gradual improvement since the beginning of the 21st century, while ratings of roads have remained at the range of "D-" and "D+" during the same period, despite all the remedial efforts to preserve road infrastructure. The rating of "D" for roads is given based on the following facts (ASCE 2017):

- More than 40% of America's urban interstates were congested in 2014;
- A total of 6.9 billion hours were wasted because of traffic delay, which equals 42 hours per driver and resulted in 3.1 billion gallons of wasted fuel in 2014. The cost associated with wasted time and fuel added up to $160 billion;
- 21% of highway pavement sections were in poor condition in 2015 and the backlog of rehabilitation needs was still increasing. Driving on these roads costs U.S. motorists $120.5 billion in extra vehicle repairs and operations in 2015; and
- Traffic fatalities increased by 7% from 2014 to 2015, as 35,092 people died on America's roads.

Infrastructure	1988	1998	2001	2005	2009	2013	2017
Bridge	-	C-	C	C	C	C+	C+
Wastewater	C	D+	D	D-	D-	D	D+
Rail	-	-	-	C-	C-	C+	B
Road	C+	D-	D+	D	D-	D	D

Table 1 Overall Condition Ratings from ASCE Infrastructure Report Card

It is also concluded that U.S. highway systems have been underfunded for years, which has resulted in an $836 billion backlog of highway and bridge capital needs. To make the situation worse, construction costs of roads are rising faster than infrastructure funding, and some states in the last five years have de-paved roads – converting asphalt roads to gravel roads where traffic is low in rural areas – to reduce material uses and maintenance needs (ASCE 2017).

On the other hand, Federal Highway Administration (FHWA) estimated that the benefits of making improvements on road infrastructure, including reduced maintenance costs, relieved delays, reduced fuel consumption and emission, and improved safety, outweigh the costs of maintenance, repair, and rehabilitation (MRR) practices by a ratio of 5.2:1 (ASCE 2017). This shows that keeping the road infrastructure in a state of good repair is not only required as a foundation for a modern society, but also preferred from an economic perspective. Therefore, the ASCE (2017) recommends that appropriate measures are taken in order to raise the grade of road infrastructure by increasing funding, raising the federal motor fuels tax, alleviating congestion, prioritizing maintenance activities, improving user safety, and making innovations in all phases of the infrastructure life cycle.

1.1.2 Transportation Infrastructure Asset Management

The American Association of State Highway and Transportation Officials (AASHTO) published Transportation Asset Management Guide: A Focus on Implementation in 2011. This guide was intended to direct agencies in successfully implementing transportation asset management at all levels in the organization through good management, effective leadership, and achieving the right organizational culture.

Transportation asset management (TAM), or transportation infrastructure asset management (TIAM) includes the systematic, coordinated planning and programming of investments or expenditures, design, construction, maintenance, operation, and evaluation of physical transportation infrastructure assets and related facilities. TAM covers activities associated with providing and maintaining transportation infrastructure assets at an acceptable level for the public, users, or owners (Uddin et al. 2013). A typical TAM system includes two interrelated levels: the network level for deficiency and need analysis, strategy evaluation, and regional prioritization; and the project level for detailed data processing, technical and economic analysis of alternatives, and implementation.

The most commonly used methodology for network-level TAM is benefit/cost analysis where benefits associated with transportation infrastructure improvement from various perspectives (e.g. user cost savings due to relieved congestion) are evaluated and compared against costs of implementing the improvement. On the other hand, for project-level TAM the tools and methods used for alternative analysis and decision-making, such as decision trees and matrices, checklists, and rating systems, vary greatly from one agency to another.

1.1.3 Sustainability in Transportation Asset Management

The concept of sustainable development was first raised by the Brundtland Report in 1987, where sustainable development was defined as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. So far, it is widely acknowledged that human activities have exerted tremendous environmental impacts by consuming non-renewable energy sources and emitting excessive amounts of greenhouse gases into the atmosphere which disturb the nature’s carbon cycles.

In the United States, the transportation sector was responsible for 27.7% of total energy consumption and 27% of CO2 emissions in 2015 (LLNL 2016; USEPA, 2016). Therefore, following a sustainable development approach in managing transportation infrastructure assets plays an important role in the overall sustainability of human activities.

The AASHTO guide (2011) dedicated one section named "Acting Sustainably" to discuss how transportation agencies may sustainably manage infrastructures that support economic growth, enable community interactions, and affect the environment. The guide provided definitions of sustainability pertaining specifically to transportation agencies under the following triple bottom line:

- Economic sustainability refers to the impact the agency has on the economics of the region and not the finances of the agency itself;
- Social sustainability refers to fair and beneficial business practices toward the community and state that balance benefits and repercussions of activities such as maintenance and construction across sociodemographic audiences; and
- Environmental sustainability is the agency's commitment to protect the environment as much as possible by doing no harm or at least by limiting its environmental impacts.

It is also perceived that energy usage, resource depletion, climate change, and other environmental issues are likely to drive changes in transportation activities and agency decision-making. Therefore, as more transportation agencies begin to appreciate the importance of sustainability and seek for improvement in sustainable development, it is becoming more important to develop a transportation infrastructure asset management framework following the triple bottom line of sustainability that can support the decision-making of public agencies.

1.2 Problem Statement and Need for Research

The aging infrastructure creates increasing economic, social, and environmental impacts on agencies and users in the United States. In order to improve the current condition of infrastructure, more frequent maintenance, repair, and rehabilitation (MRR) activities are expected to take place in the near future. Therefore, infrastructure management frameworks that support agency decision-making processes are expected to play a more central role.

While significant advancements have been achieved in accelerated construction of bridges using prefabricated elements, accelerated methods, and other innovative techniques and equipment, the MRR activities for roadways are still mostly undertaken by traditional methods, resulting in high user costs and environmental impacts due to prolonged traffic disruptions. To improve current practices, an infrastructure management framework for roadways with the capability of evaluating non-traditional techniques including accelerated methods is needed to support decision-making of public agencies.

Because of their broader scope, network-level road infrastructure management systems usually take into consideration benefits such as user cost saving, user emission reduction, and other social or environmental factors. On the other hand, at the project level, existing decision support frameworks including software programs, department guidelines, and decision trees and matrices are mostly agency oriented and cost driven; insufficient attention has been paid to the social and environmental impacts of project-level decisions. In addition, existing decision support tools utilized by public agencies were mostly developed in late 1990s or early 2000s and have not been updated in a timely manner. These tools incorporate very few alternatives using non-traditional techniques and fail to cover a sufficient number of important factors from different perspectives for the selection of alternatives.

Meanwhile, some non-traditional MRR techniques such as intelligent compaction do not have unified design procedures or measures of reporting; and each project has been performed differently based on specific conditions. This makes it challenging for public agencies to adopt these techniques due to a lack of frameworks that can quantitatively analyze their overall impacts and justify their implementation at a project level.

As a result, there is a need for a project-level roadway infrastructure management framework that comprehensively covers various MRR techniques, considers multiple factors from the economic, social, and environmental aspects in decision-making, and provides quantitative analysis on a life-cycle basis to evaluate the sustainability of alternatives.

1.3 Research Questions, Goals, and Objectives

With the research needs identified, the following two major research questions are formulated: (1) how can various economic, social, and environmental factors be considered in project-level decision-making, and (2) how can project-level maintenance, repair, and rehabilitation alternatives be evaluated using a life-cycle approach?

Therefore, the goal of this research is to develop a project-level roadway infrastructure management framework to assist public agencies in the selection of the most appropriate maintenance, repair, and rehabilitation alternatives, especially non-traditional alternatives including accelerated methods, under the triple bottom line of sustainability. Roadway infrastructure is selected as the research subject due to its high importance in overall infrastructure assets and a lack of innovation in project-level infrastructure management practices compared to other types of infrastructure.

To achieve the research goal, the following research objectives were accomplished:

- Investigate current practices of transportation agencies in infrastructure management and sustainability;
- Study traditional and non-traditional roadway MRR techniques including accelerated methods, such as warm mix asphalt (WMA) overlay, cold-in-place recycling (CIR), full depth reclamation (FDR), intelligent compaction (IC), and precast concrete pavement system (PCPS);
- Evaluate project-level alternatives considering various economic, social, and environmental factors;
- Analyze project-level alternatives with a life cycle approach according to the triple bottom lines of sustainability through life cycle assessment and life cycle cost analysis.

1.4 Research Methodology

The proposed project-level infrastructure management framework consists of two decision flowcharts (one for flexible pavements and the other for rigid pavements), a multi-criteria decision making (MCDM) model, and a life cycle assessment (LCA) and life cycle cost analysis (LCCA) model. A schematic diagram of the overall framework is shown in Figure 1.

The MCDM model includes a total of twelve factors from technical, economic, social, and environmental perspectives to make preliminary project-level decisions. Weights of the criteria are determined by the survey results by Salman et al. (2017) through analytical hierarchy process (AHP) and analytical network process (ANP).

The LCA-LCCA model further evaluates project-level alternatives and makes decisions according to the agency’s sustainability goals and performance measures. Software programs and databases including GREET®[1], MOVES[2], and Athena Pavement LCA are used for life cycle assessment while survey results by Salman et al. (2017), RSMeans 2016[3], and other miscellaneous cost sources are used for LCCA, respectively.

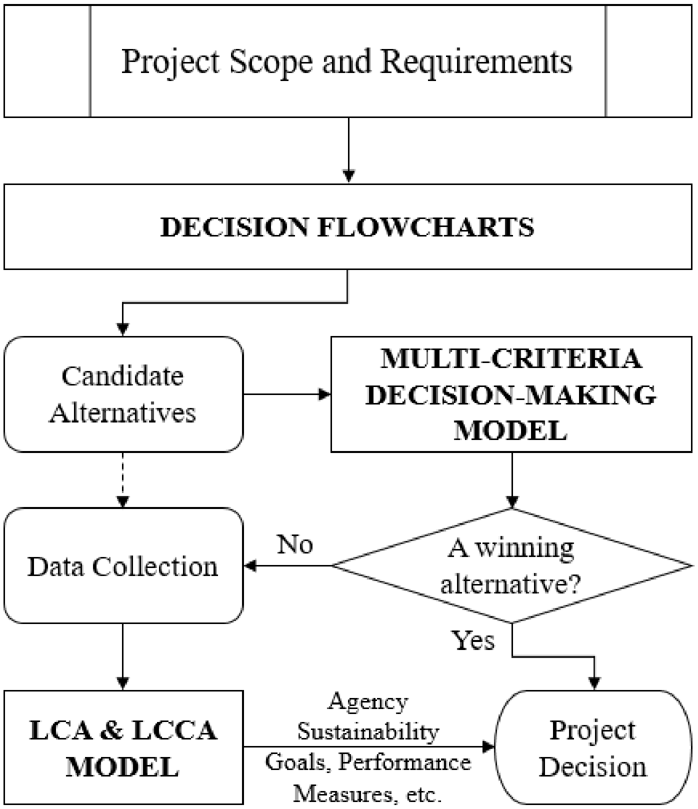

Figure 1 Project-level Decision Support Framework Schematic Diagram

Demonstration case studies (two for the MCDM model and two for the LCA-LCCA model) are used to elaborate on the proposed decision support framework, while validations are performed through expert opinions for the decision flowcharts and MCDM model, and through literature contrast for the LCA-LCCA model.

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[1] Greenhouse gases, Regulated Emissions and Energy in Transportation (GREET®) model by Argonne national laboratory (ANL) is a life cycle inventory database of transportation fuels and other products.

[2] MOVES (Motor Vehicle Emission Simulator) by EPA estimates emissions from mobile sources.

[3] RSMeans by GORDIAN® estimates construction costs.

1.5 Discussion, Conclusions, and Future Studies

This research is expected to fill the gap of a comprehensive project-level roadway infrastructure management framework under the triple bottom line of sustainability and to provide suggestions to public agencies regarding the contents and approaches needed for project-level decision-making. It also takes an initiative to evaluate non-traditional MRR techniques, including accelerated methods, and to improve commonly used MCDM methods in modeling problems associated with infrastructure management decision-making.

The proposed decision support framework is capable of quantifying the overall and specific impacts of project alternatives using non-traditional MRR techniques including accelerated methods. Results of the demonstration case study for the LCA-LCCA model show that compared to traditional techniques, project alternatives using HIPR, CIR and FDR significantly reduce life cycle costs and environmental impacts, while the WMA overlay and IC alternatives deliver limited overall impact reductions. PCPS also considerably lowers environmental impacts. These findings are in good consistency with existing literature. Using this framework, public agencies should apply their own data, study the economic, social, and environmental impacts of project alternatives, and make decisions based on agency goals, objectives, and performance measures to improve the overall sustainability.

The IC project alternatives can be revisited once additional benefits of applying intelligent compaction are reported. Future studies may expand this decision support framework by including more criteria in MCDM and analyzing more roadway, vehicle, and fuel types for LCA-LCCA model.

2 LITERATURE REVIEW

2.1 Infrastructure Asset Management and Sustainability

With limited funding and an increasing backlog of rehabilitation requirements, transportation agencies need to plan MRR work to achieve optimum cost effectiveness, and this is one of the major objectives of infrastructure asset management. Infrastructure asset management (IAM) includes the systematic coordinated planning and programming of investments or expenditures, design, construction, maintenance, operation, and evaluation of physical infrastructure assets and related facilities. It covers all the activities associated with providing and maintaining infrastructure assets at a level of service acceptable to the public, users, or owners. An infrastructure asset management system (IAMS) coordinates and enables the execution of these activities so that the use of available funds is optimized and the performance and preservation of infrastructure assets and provision of services are maximized (Uddin et al. 2013).

An overall framework for an IAMS is shown in Figure 2. IAM efforts are undertaken at two interrelated levels: the program/network/system-wide level and the project/section level. Both levels have respective components, objects, and external constraints that are usually beyond the control of agencies. The scope of an IAMS depends on the network size and service boundaries under the agency's jurisdiction. While an IAMS has a generic scope across all types of infrastructure, particular models, methods, and procedures are different from one to another (Uddin et al. 2013). Therefore, there are IAMSs specifically developed and utilized for roadways, bridges, underground utilities and others. Figure 3 shows a two-level IAMS framework for roadway pavement management (Haas 1994).

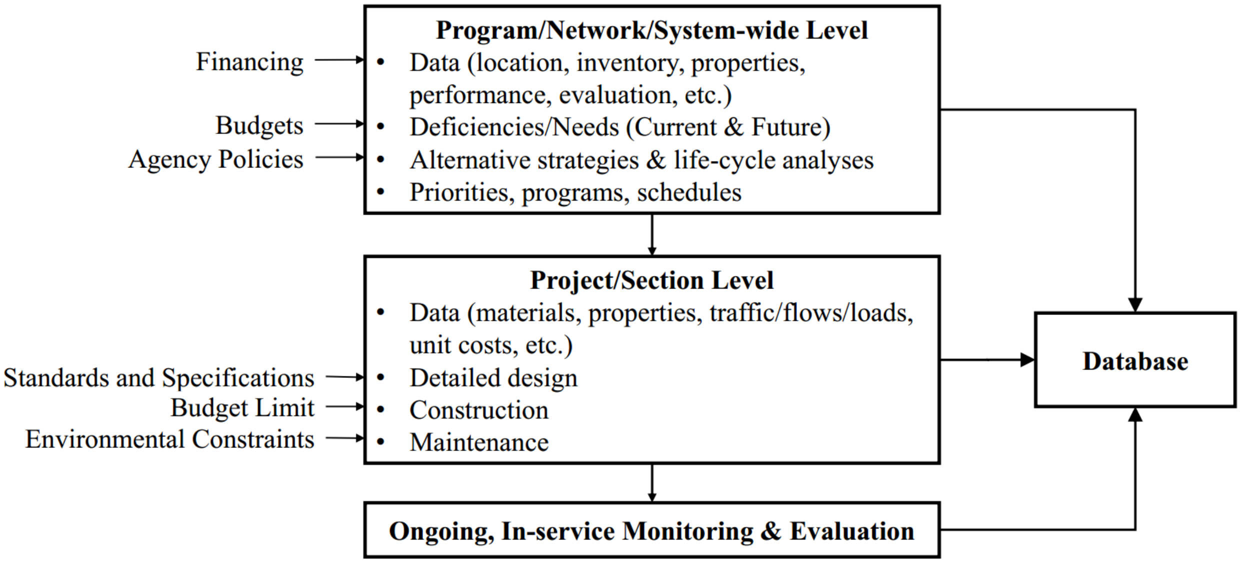


Figure 2 Overall framework for infrastructure asset management

Adapted from Uddin et al. (2013)

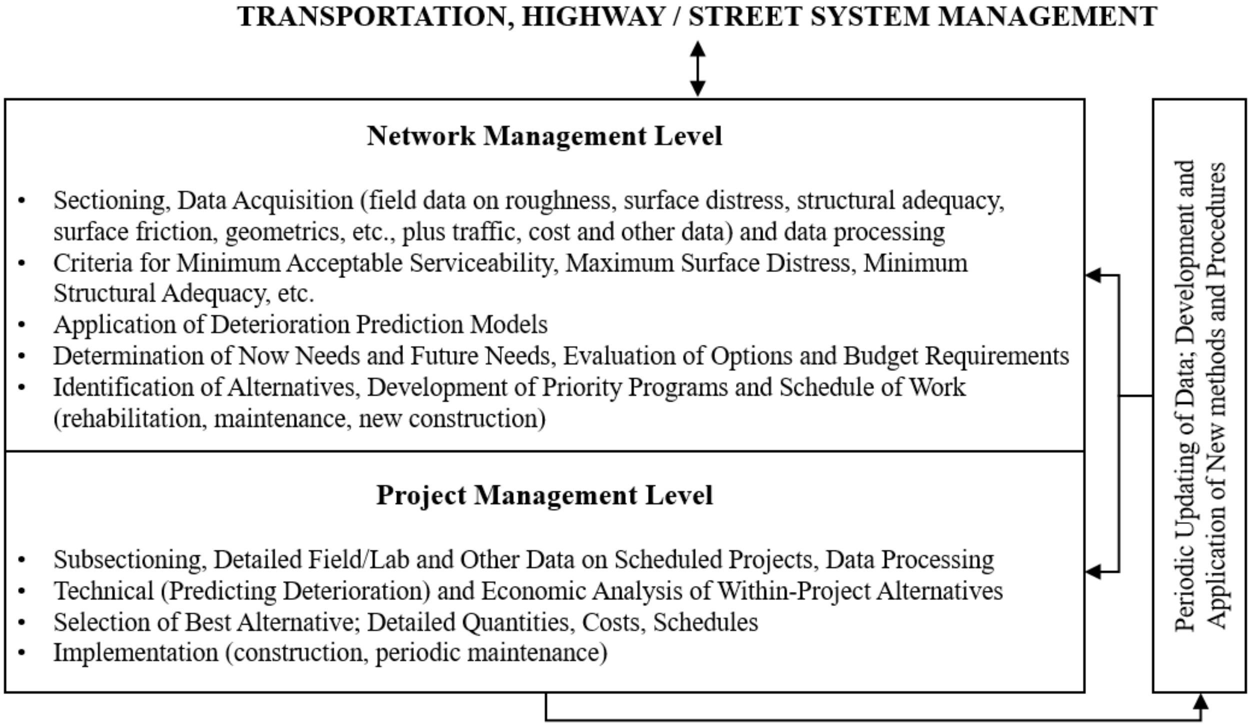


Figure 3 Operating levels of pavement management and major activities

Adapted from Haas (1994)

2.1.1 Network-Level Infrastructure Asset Management

At the network level, focuses are placed on deficiency and need analysis, strategy evaluation, and regional prioritization. General frameworks and guidelines for network-level IAMS have been provided by American Association of State Highway and Transportation Officials through the *AASHTO Transportation Asset Management Guide: A Focus on Implementation* (2011). The guide covers both managerial and technical aspects of infrastructure asset management and is expected to assist decision makers at state, county, and municipal levels in achieving IAM goals. Federal Highway Administration (FHWA) also urged the development and adoption of Transportation Asset Management Plans (TAMP) for state departments of transportation (DOT) as a response to the clause that states, “Each State is required to develop a risk-based asset management plan for the National Highway System to improve or preserve the condition of the assets and the performance of the system” (23 U.S.C. 119(e)(1), MAP-21 § 1106).

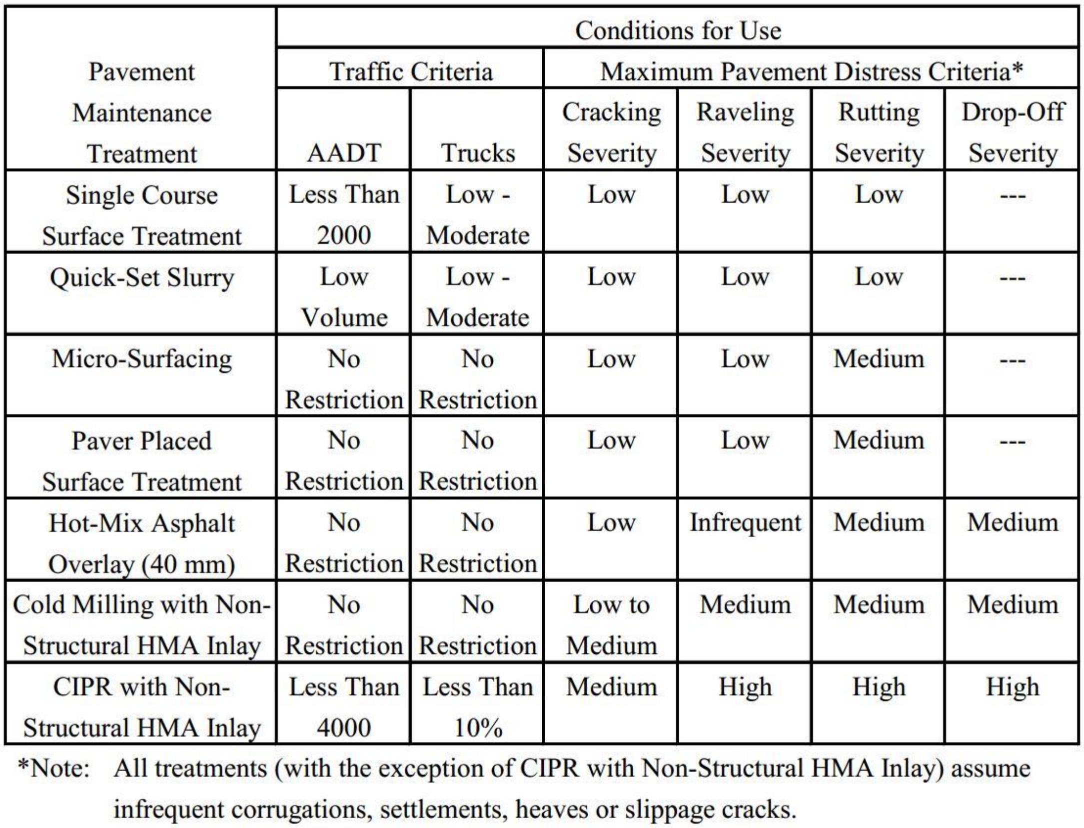
Several studies have been conducted recently on IAMS for different types of infrastructure assets on a network level. To name a few, Zhang et al. (2013) developed a network-level IAMS for pavements; Arif et al. (2016) proposed a multi-criteria decision support framework for MRR of bridges; Chuang et al. (2006) presented a decision-making framework for underground sewer pipelines; Bhattachar et al. (2007) proposed a framework for inventory and inspection of culvert infrastructure; Salman and Salem (2012) developed a risk assessment tool for managing wastewater collection lines; and Bernhardt et al. (2003) generated an IAMS for geotechnical assets based on the general framework by FHWA. It should also be noted that some IAMSs proposed for one type of infrastructure asset may be utilized to analyze other assets, and there are also other research (Hsieh and Liu 1997; Sadek et al. 2003; Hastak et al. 2005; ASME 2009) on IAMSs in general without referring to specific types of infrastructure.

2.1.2 Project-Level Infrastructure Asset Management

At the project level, on the other hand, IAM performances vary greatly depending on the types of infrastructure and the operations of responsible public agencies. As a result, there are not as many studies specifically on the project-level IAM as those on the network-level IAM, while some decision support frameworks developed primarily for network-level prioritization are reported to be able to provide project-level analysis for the selection of alternatives. Other than the network-level IAMS research discussed before, Elbehairy et al. (2009) proposed a bridge management system that achieves both network-level and project-level optimization.

In the context of pavement IAMS at the project level, as shown in Figure 3, after the network-level prioritization is completed and the sections of roadway to be maintained, repaired, or rehabilitated are identified, regional transportation agencies will continue to plan and execute corresponding activities. Commonly used tools that can assist regional transportation agencies in developing and evaluating alternatives include public and/or private software programs, department-specific guidelines, decision trees, and decision matrices, all of which may be part of the pavement management system (PMS) utilized by the agency. Most software programs allow agencies to analyze different maintenance strategies under different budget scenarios, and some feature integration with geographic information system (GIS) to provide visualization of infrastructure assets.

Guidelines, decision trees, and decision matrices are usually developed according to the specific characteristics of the roadway infrastructure managed by the agency. Figure 4 shows a decision matrix used by NYSDOT for project-level management of flexible pavement infrastructure (Hicks et al. 2000), in which a total of seven alternatives are included and information regarding traffic and distress are considered in decision-making process. These types of decision trees and matrices usually provide limited numbers of alternatives and consider few factors other than pavement distress types and severities.



Pavement Maintenance Treatment	Conditions for Use					
	Traffic Criteria		Maximum Pavement Distress Criteria*			
	AADT	Trucks	Cracking Severity	Raveling Severity	Rutting Severity	Drop-Off Severity
Single Course Surface Treatment	Less Than 2000	Low - Moderate	Low	Low	Low	---
Quick-Set Slurry	Low Volume	Low - Moderate	Low	Low	Low	---
Micro-Surfacing	No Restriction	No Restriction	Low	Low	Medium	---
Paver Placed Surface Treatment	No Restriction	No Restriction	Low	Low	Medium	---
Hot-Mix Asphalt Overlay (40 mm)	No Restriction	No Restriction	Low	Infrequent	Medium	Medium
Cold Milling with Non-Structural HMA Inlay	No Restriction	No Restriction	Low to Medium	Medium	Medium	Medium
CIPR with Non-Structural HMA Inlay	Less Than 4000	Less Than 10%	Medium	High	High	High

*Note: All treatments (with the exception of CIPR with Non-Structural HMA Inlay) assume infrequent corrugations, settlements, heaves or slippage cracks.

Figure 4 NYSDOT decision matrix on alternative preventive maintenance treatments

Economic analysis is usually performed to determine the viability and timing of a project and to achieve maximum cost effectiveness once a project has been selected and budgeted. The basic principles of economic analysis at network level and project level are the same, but the amount of detail and information is more extensive at the project level where alternatives are developed and compared with each other. Uddin et al. (2013) suggest that it is highly important to include the costs and benefits over the entire life cycle of an infrastructure asset from as many aspects, such as agency, user, and environment, as possible in the economic analysis, so that non-traditional alternatives that may not be selected based on initial cost alone can be justified.

2.1.3 Sustainable Practices in Transportation Infrastructure Asset Management

The AASHTO (2011) guide pointed out that transportation agencies need to understand the effect of transportation services on the environment and that of climate change on transportation infrastructure. Another guide was developed through the National Cooperative Highway Research Program (NCHRP) in 2011 to assist transportation agencies in identifying and applying sustainability performance measures. These guides provide frameworks in which transportation agencies could develop appropriate infrastructure asset management plans and make necessary adjustment to existing managerial and organizational structures to incorporate sustainability at an enterprise/network/program level.

Commonly used sustainability-oriented decision support tools for agencies' decision-making in infrastructure management are self-evaluation or third-party certification sustainability rating systems that evaluate the overall sustainability of projects under the triple bottom line through credit assignment. A selection of sustainability rating systems discussed in the AASHTO guide (2011) is provided in Table 2.

It is observed that these sustainability rating systems mostly use points or ordinal rankings to describe project sustainability, and scoring procedures rely largely on subjective evaluation. Therefore, the results of such a rating system, either in the form of total scores or corresponding levels of achievement, bear limited practical implications beyond the system itself. On the contrary, a framework that quantifies the economic, social, and environmental impacts in their original forms provides agencies with more accurate and meaningful results, which facilitates the achievement of agencies' sustainability goals and objectives following the AASHTO guide.

Table 2 Selected Sustainability Rating Systems

Rating Systems	Developed by	Key Characteristics	References
INVEST (Infrastructure Voluntary Evaluation Sustainability Tool) v1.2	FHWA	Self-evaluation tool, 68 criteria in three categories (system planning for states, system planning for regions, project development, operations and maintenance, and Innovative)	FHWA (2017)
ENVISION v2.0	Institute for Sustainable Infrastructure	Self-evaluation tool; 60 sustainability criteria from five categories (quality of life, leadership, resource allocation, natural world, and climate & risk). Five levels of achievement for each criteria (improved, enhanced, superior, conserving, and restorative). Maximum total points: 809.	Institute for Sustainable Infrastructure (2017)
Sustainable Transportation Access Rating System (STARS)	North American Sustainable Transportation Council	Third-party certification; 29 credits in six categories (integrated process, access, climate and energy, ecological function, cost effectiveness analysis, and innovation)	Hurley (2010)
Greenroads v1.5	University of Washington, CH2M HILL	Voluntary rating system; 37 credits that total 108 points plus 10 more custom points with 1 to 5 points under each credit out of seven components (ecology, equity, economy, extent, expectations, experience, and exposure)	University of Washington (2011)
Green Leadership in Transportation and Environmental Sustainability (GreenLITES) v2.1.0	NYSDOT	Self-certification; similar to Greenroads with five categories (sustainable sites, water quality, materials and resources, energy and atmosphere, and innovation/unlisted)	NYSDOT (2017)
Illinois Livable and Sustainable Transportation System and Guide (I-LAST) v 2.02	IDOT, ACEC-IL[4], and IRTBA[5]	Percentage-based evaluation tool; 20 credits in eight categories (planning, design, environmental, water quality, transportation, lighting, materials, and innovation)	IDOT (2012)
Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways (BE^{2}ST-in-Highways)	University of Wisconsin-Madison	Customizable weighting tools using analytical hierarchy process; nine criteria; stakeholders can select weights and credits based on relative importance	University of Wisconsin-Madison (2017)
Green Guide for Roads	Transportation Association of Canada	Self-evaluation tool; three-point ranking (high, medium, low) of 13 areas.	Transportation Association of Canada (2015)
GreenPave	Ministry of Transportation of Ontario, Canada	Points-based system, similar to Greenroads and GreenLITES with customization for Ontario	Chan et al. (2013)

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[4] American Council of Engineering Companies-Illinois

[5] Illinois Road and Transportation Builders Association

2.2 Roadway Maintenance, Repair, and Rehabilitation Techniques

Pavement preservation activities are generally categorized into preventative maintenance, routine maintenance, repair, rehabilitation, and reconstruction activities. Other terms such as restoration and remodeling are also used interchangeably. Uddin et al. (2013) provide definitions of these different actions:

- ***Maintenance*** *is the set of activities required to keep a component, system, infrastructure asset, or facility functioning as it was originally designed and constructed to function.*
    - *Preventive or proactive maintenance, or preservation, is performed to retard or prevent deterioration or failure of a component or system;*
    - *Corrective or reactive maintenance is performed to repair damage and/or to restore infrastructure to satisfactory operation or function, after failure.*
    - *Routine maintenance is any maintenance done on a regular basis or schedule. In nature it is generally preventive, but it can also be corrective.*
- ***Rehabilitation*** *is the act or process of making possible a compatible use for a property through repair, alternations, and additions, while preserving those portions or features that convey its historical, cultural, or architectural values.*
- ***Reconstruction*** *is the act or process of depicting, by means of new construction, the form, features, and detailing of a non-surviving site, landscape, building, structure, or object, for the purpose of replicating its appearance at a specific period of time and in its historic location.*

In this research, non-traditional MRR techniques refer to the processes and procedures that achieve goals and objectives of maintenance, repair, and rehabilitation with reduced economic, social, and/or environmental impacts in comparison to the traditionally used techniques, In some states, non-traditional techniques have been performed more extensively than others, as different public agencies in the United States vary greatly in the adoption of non-traditional MRR techniques.

As maintenance and repair techniques usually result in relatively small overall impact, more emphasis has been exerted on improving rehabilitation/reconstruction techniques for roadways. Therefore, non-traditional MRR techniques covered in this study are mostly rehabilitation techniques including warm mix asphalt (WMA) overlay, cold-in-place recycling (CIR), full depth reclamation (FDR), innovative compaction (IC) for flexible pavements, and use of precast concrete pavement systems (PCPS) for rigid pavements. The traditional techniques, as the counterparts of non-traditional ones, are hot mix asphalt (HMA) overlays and hot-in-place recycling (HIPR) for flexible pavements and use of cast-in-place (CIP) concrete for rigid pavements. This research also covers maintenance and repair treatments such as crack seal, asphalt patching for flexible pavements, and crack repair and diamond grinding for rigid pavements. Detailed information on traditional and non-traditional techniques is provided in the following subsections.

2.2.1 Traditional Techniques

2.2.1.1 Crack Seal and Joint Seal

Crack seal is used for addressing cracks on asphalt pavement surfaces to reduce infiltration of water into the pavement through cracks and slow surface deterioration. The most commonly used materials in crack sealing procedures are bituminous sealants. Sealants are usually formulated with bitumen, a polymer modifier such as styrene-butadiene-styrene, and recycled-rubber powder (Wang et al. 2012). Crack seal is capable of treating minor to moderate cracking problems at an acceptable cost, but it usually makes very limited extension to the service life of asphalt pavement. Joint Seal for concrete pavement is performed out of the same consideration as crack seal for asphalt pavement. It is needed when missing or de-bonded sealants or seal joints containing incompressible objects are present (FHWA 2005).

2.2.1.2 Patching

Pavement patching is performed by removing a distressed area and then backfilling with new asphalt or concrete mixture, which addresses local pavement deficiencies. Patching is also needed if areas of distresses exist while the entire pavement section requires rehabilitation as a pre-overlay repair method (Li and Wen 2014).

2.2.1.3 Hot Mix Asphalt Overlays

Hot Mix Asphalt (HMA) Overlays replace the top layers of deteriorated asphalt pavement with a new hot mix asphalt layer typically with lift thickness of from 1.25 to 2 inches, which substantially increases the service life of pavement (by eight to ten years). On other occasions, HMA overlays of thinner lifts, from 0.5 to 1.25 inches, are used to achieve higher cost efficiency if thin overlays are effective in addressing pavement distresses (Wilson et al. 2015).

2.2.1.4 Diamond Grinding

Diamond grinding is a concrete pavement restoration technique that addresses faulting and roughness irregularities to restore rideability, increase surface macro-texture, reduce noise, and improve safety, which is typically used in conjunction with other concrete pavement rehabilitation techniques. The reduction of slab thickness by diamond grinding is generally between 3/16 and ¼ inch, and the effect on service life due to reduction of thickness is reported to be negligible (Correa and Wong 2001).

2.2.2 Warm Mix Asphalt

Warm mix asphalt (WMA) refers to asphalt mixtures that are produced at lower temperatures than those typically used in the hot mix asphalt (HMA) production, usually by 50°F or more. This is achieved through asphalt foaming technologies or by using organic or chemical additives.

First introduced in Europe in the late 1990s, WMA was intended to reduce greenhouse gas emissions while providing mixtures with similar strength, durability, and performance characteristics as traditional HMA because of the substantially reduced production temperature (Bonaquist 2011). The first WMA pavement in the United States was constructed in 2004, followed by a large number of field trials (West et al. 2014).

Benefits of using WMA as a substitute of traditional HMA include reduced fuel use and plant emissions, improved working conditions, better workability and compaction, extended paving season due to increased potential for cool weather paving, and increased amount of allowable reclaimed asphalt pavement to be used (Anderson et al. 2008).

2.2.3 Cold-in-Place Recycling

Cold-in-place recycling (CIR) refers to a rehabilitation process in which the existing pavement materials are reused in-place without applying heat. This technique proves to be very effective in addressing asphalt pavement deficiencies such as cracking, rutting, bumping and shoveling (Gao et.al 2014).

Specific steps of performing CIR include milling up the existing asphalt pavement, sizing the aggregates, mixing with an emulsified asphalt or active filler, placing the new asphalt mix, and compacting the materials. Recycling agents such as lime, fly ash, cement, lime kiln dust, foamed asphalt, or asphalt emulsion are used for the CIR technique in order to achieve proper binding in the asphalt mixture. Foamed asphalt is produced when asphalt cement is heated and pumped through an expansion chamber on the cold recycling unit, where a small amount of cold water is injected and vaporized, causing the asphalt cement to rapidly foam (Lane and Lee 2014).

Shorter construction periods, reduced transportation and production of virgin materials, and reduced fuel consumptions and greenhouse gas emissions are the most widely recognized benefits of using CIR. Meanwhile, because of the absence of heating, reclaimed asphalt pavement materials in CIR are subject to minimum aging, making it possible to perform another CIR treatment once the previously CIR-treated pavement reaches the end of its service life (Lane and Lee 2014).

2.2.4 Full Depth Reclamation

Full depth reclamation (FDR) is the process where the entire thickness of the distressed pavement and a pre-determined amount of the subbase layer or base layer are uniformly pulverized and mixed together to form a stabilized base course. This rehabilitation technique is typically used when (1) target pavement sections demonstrate extensive structural distresses, (2) deficiencies occur at lower layers of the pavement, or (3) pavement sections reach the end of their service lives (Swiertz 2015). Stabilizing agents used in FDR are essentially the same as recycling agents used in CIR such as active fillers, asphalt emulsion, and foamed asphalt, which aim at restoring the mechanical deficiencies of reclaimed materials and improving the structural characteristics of the base or subbase layer.

The main advantage of FDR technique is that it eliminates potential structural deficiencies in lower layers of asphalt pavement, which contribute to the formation of reflective cracks and other distresses resulting from base or subbase layer problems. Therefore, when severe structural failure occurs, FDR is usually a preferable option to conventional rehabilitation techniques from a life-cycle perspective because of the reduced future maintenance costs (Bocci et.al 2012). As one of the recycling techniques, FDR also decreases the use and transportation of virgin materials, resulting in reduced construction costs and greenhouse gas emissions.

2.2.5 Intelligent Compaction

Intelligent compaction (IC) technique refers to the process where compaction is monitored and controlled by instrumentations to achieve more uniformed compaction and 100% coverage of the compacted area rather than through the point measurements of traditional stiffness and density tests for quality assurance. Intelligent compaction was introduced in the United States in 2004 following its successful implementation in Europe, but its adoption has been relatively slow ever since (Mooney et al. 2010).

Major components of an IC system include a global positioning system (GPS), accelerometer, infrared temperature sensor, processing software, visual display, and data storage (Mooney et al. 2010). Through the functionalities of these system components, IC allows paving contractors to closely monitor the stiffness of the materials being compacted in order to minimize variability in the end product. As a result, fewer roller passes are needed to achieve the desired level of compaction, which leads to optimized labor utilization, shortened construction time, reduced fuel consumption, and minimized equipment wear-and-tear.

IC also offers identification of the areas that have not been properly compacted so that reworking of the defective compaction can be planned before additional layers are placed to avoid problems in subsurface layer once compaction is completed. This reduces maintenance requirements and generates construction records for future reference, making it a favorable addition to traditional paving process from a life-cycle perspective. Meanwhile, one limitation of IC application is that there is not yet an industrial standard on the generation and reporting of compaction information (Savan et al. 2015).

2.2.6 Precast Concrete Pavement Systems

Unlike the traditional cast-in-place process, precast concrete pavement (PCP) systems use concrete slabs fabricated off-site and transported to the project site to construct or rehabilitate rigid pavement sections. Precast concrete slabs are usually installed on prepared foundations, and no on-site curing is needed to achieve sufficient strength. Construction can take place during off-peak hours or even overnight for minimum disturbance to traffic. As a result, PCP systems are most suitable for the rehabilitation of rigid pavements serving heavy traffic for congestion reduction considerations.

Other than shortening of the construction schedule, PCP systems also allow a higher standard of quality and fabrication because concrete slabs and panels are manufactured off-site with potentially improved quality control, which reduces future maintenance needs and increases infrastructure service life (FHWA 2017).

In summary, non-traditional MRR techniques for roadways may reduce construction costs, duration, fuel consumption, greenhouse gas emission, and use of virgin materials. More importantly, these techniques are most likely going to create life cycle cost savings, which could be a good justification of their implementation.

Table 3 shows the documented benefits of non-traditional MRR techniques for roadways.

Table 3 Summary of Benefits of Non-traditional MRR Techniques for Roadways

Benefits	WMA	CIR	FDR	IC	PCPS
Construction Cost Savings	√		√		
Life-Cycle Cost Savings	√	√	√	√	√
Accelerated Construction		√		√	√
Improved Working Condition	√	√			
Improved Quality			√	√	√
Reduced Fuel Consumption	√	√	√	√	
Reduced GHG Emissions	√	√	√	√	
Reduced Virgin Materials		√	√		

2.3 Multi-Criteria Decision-making Methods

Multi-criteria decision-making (MCDM) refers to making decisions in the presence of multiple, usually conflicting, criteria (Tzeng and Huang 2011). In the context of project-level infrastructure asset management, one example is that accelerated construction techniques for roadways may on one hand incur higher agency costs because of extra labor and equipment but will, on the other hand, reduce user costs due to a shortened construction schedule and alleviated congestion in the vicinity of work zone. Therefore, maintenance, repair, and rehabilitation techniques and alternatives have profound impacts on the economy, society and environment, and it is highly recommended that decision makers take important factors from all aspects into consideration.

Based on the review from Mardani et al. (2015), the most commonly used MCDM methods since 2000 are the Analytical Hierarchy Process (AHP), Analytical Network process (ANP), Technique for Order Performance by Similarity to Ideal Solution (TOPSIS), and ELimination Et Choix Traduisant la REalité (ELECTRE). There are also many other studies using hybrid methods by combining two or more basic MCDM methods or other updated and improved MCDM methods.

2.3.1 Analytical Hierarchy Process

Analytical Hierarchy Process (AHP) is a flexible pairwise comparison model developed by Saaty (1970). It can be used to model a wide range of problems in an easily understandable way, while incorporating logic, intuition, experience, judgment, and personal values in the analysis and considering all factors to reach to a final conclusion.

AHP starts with defining hierarchies to structure the problem so that a clear understanding of relationships is obtained and factors can be identified and compared on the same platform. Factors are categorized in groups that logically relate to the higher level so that the relative importance of each factor and group can be calculated. Once the hierarchic structure with major factors is developed, priorities are assigned to elements for each criterion on the higher level followed by a weighting process on the lower level.

To list a few applications of AHP in construction and project management, Gudienė et al. (2014) evaluated factors affecting construction projects in Lithuania; Salem (2013) modeled decisions on accelerated bridge construction; Raviv et al. (2017) analyzed the risk potential of safety incidents, and Inti et al. (2016) used modified AHP to support decision-making processes in pavement design selection.

Benefits of using AHP include the ability to model various unstructured problems with ease, the similarity to the natural tendencies of the human rational thinking process, the capability of measuring intangible factors, and flexibility of customization by adjusting relative priorities to match the changing goal (Saaty 1982). AHP, however, works with the assumption that one element is independent from other elements on the same level and on lower levels. This may not be in strict consistency with the nature of the problem to be modeled.

2.3.2 Analytical Network Process

Analytical network process (ANP) provides a general framework in the form of a network for dealing with decisions without making assumptions about the independence of higher-level elements from lower level elements and about the independence of the elements within a level as in a hierarchy. The difference between the two MCDM methods regarding composition is shown in Figure 5.

In ANP, one needs to make judgment regarding the relative importance of two elements, similar to the pairwise comparison process in AHP, and also regarding their relative influences on a third element with respect to a criterion (Saaty 2004). In this manner, with more intensive calculation requirements, ANP is capable of analyzing the dependency between and among alternatives and criteria, and it is believed to provide more accurate modeling results under complex decision-making conditions.

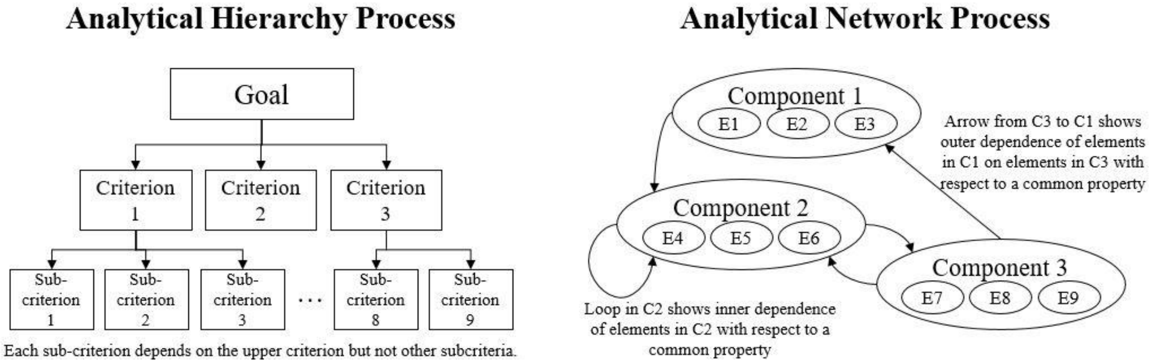

Figure 5 Hierarchy and Network

General steps in modeling MCDM problems using ANP include (Saaty 2004): (1) development of a decision model structure, (2) conducting pairwise comparisons on clusters and nodes, (3) forming the supermatrix that includes relative weights of sub-matrices from pairwise comparison results, (4) normalizing supermatrix to obtain stochastic columns, and (5) raising the supermatrix to limiting powers until the weights have converged.

Because of the capability of modeling interdependencies of elements, especially the feedback effect from low-level factors to high-level factors, the ANP method is adopted in decision environments where influences of criteria and alternatives on each other cannot be overlooked. For example, Zhou and Yang (2011) assessed risk associated with a new campus construction project with fuzzy ANP; Atmaca and Basar (2012) used ANP to evaluate alternatives of different types of power plants considering various factors including economy, technology, and sustainability; and Xu et al. (2015) analyzed interrelationships of factors affecting sustainable building energy efficiency retrofit.

2.3.3 Technique for Order Performance by Similarity to Ideal Solution

The basic principle of the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) method proposed by Hwang and Yoon (1981) is that the chosen alternative has the shortest distance from the ideal solution and the farthest distance from the negative ideal solution to reflect the optimization by decision-making. Major procedures of TOPSIS method include developing normalized and weighted normalized decision matrices, determining the ideal and negative-ideal solutions, and calculating separation measures and relative closeness to the ideal solution (Opricovic and Tzeng 2004).

This method is particularly suitable for decision-making scenarios where a large number of attributes and alternatives are present with objective and quantitative data (Shih et al. 2007). For example, Srdjevic et al. (2004) evaluated water management scenarios with TOPSIS; Janic (2003) applied TOPSIS in the selection of high-speed transport systems; and Cheng et al. (2002) used TOPSIS to analyze solid waste management.

2.3.4 ELimination Et Choix Traduisant la REalité

Since the development of the ELimination Et Choix Traduisant la REalité (ELECTRE) method by Roy (1968), there have been many versions of ELECTRE method with different operations and targeted types of problems, but the fundamental concepts of these versions are the same: thresholds and outranking. In the original ELECTRE method, the decision maker will specify an indifference threshold and a weak preference threshold to indicate the different levels of preferences in evaluating two alternatives. Then each criterion is examined for concordance or discordance with the determination of preference and has a concordance index calculated to form a matrix of preferences and alternatives.

The effectiveness and accuracy of analysis depends heavily on the assignment of threshold values. One advantage of the ELECTRE method is its direct use of objective/numerical data while most other MCDM methods rely on subjective/nominal data from decision maker preferences (Buchanan et al. 1998).

Popular application areas for the ELECTRE family include natural resources and environmental management, business management, energy management, design, mechanical engineering and manufacturing, and construction engineering (Govindan and Jepsen 2016). Examples related to infrastructure asset management include evaluation of transport projects by Tsamboulas, et al. (1999), risk assessment of pipelines by Brito et al. (2010), and evaluation of cross-country transport-sustainability by Bojkovic et al. (2010).

Table 4 summaries characteristics, advantages, and limitations of MCDM methods. Based on the research objectives, ANP is the most suitable method because of its capability of analyzing interdependencies among factors from a triple bottom line of sustainability.

Meanwhile, using AHP allows users to customize the decision support tool due to ease of use and understanding. TOPSIS is less applicable because there are usually not a great number of project alternatives for analysis. Determination of threshold values for ELECTRE method is also challenging, making it inappropriate for this research.

Table 4 Characteristics of Common MCDM Methods

Methods	**AHP**	**ANP**	**TOPSIS**	**ELECTRE**
Feature	Hierarchy structure; weights assigned to each criterion	Network form; model influences among elements	Select the one with shortest distance to ideal solution	Use thresholds and outranking to evaluate alternatives
Advantage	Ease of use and understanding	Can analyze dependencies	Good for large number of alternatives	Direct use of numerical data
Limitation	Assumption of independence	High complexity	Number of alternatives	Dependent on threshold values

2.4 Life Cycle Assessment and Life Cycle Cost Analysis

2.4.1 Life Cycle Assessment

Life cycle assessment (LCA) is a "cradle-to-grave" approach for assessing products and systems by evaluating the environmental impacts resulting from all stages throughout the entire life cycle. A typical LCA, also known as a process-based LCA, defined by EPA and ISO 14040, consists of four components including goal definition and scoping, inventory analysis, impact assessment and interpretation. If conducted properly, LCA allows users to compare all major environmental impacts of different alternatives and avoid biased results due to certain portions of environmental impacts being excluded from the study. Therefore, users of LCA need to have a well-defined scope and complete and up-to-date data in order to produce accurate final results, which makes the performance of an LCA highly resource intensive (SAIC 2006).

To simplify the procedures of defining the analysis boundary and collecting comprehensive data in process-based LCA, the economic input-output (EIO) LCA model was developed by Carnegie Mellon University (2009) to show what outputs of an industry are used as inputs of other industries. By using this linear impact model, users can estimate the overall environmental impacts from producing a certain value of commodities or services in the United States. With a very broad coverage, the EIO LCA model is capable of not only investigating environmental impacts of cross-sector products but also identifying the effect of changes on the economy.

However, due to its matrix form, customization of the EIO LCA model is highly challenging. In addition, there is no further differentiation within a single industry, making it difficult to evaluate environmental impacts of specific products or services on a small scale. Therefore, to perform the life cycle assessment of roadway infrastructure asset management where various MRR activities are involved, a process-based LCA approach is more appropriate in order to capture the uniqueness of each project-level alternative. Recent studies on life cycle assessment of roadway pavement, some of which are summarized in Table 5, are largely undertaken by process-based LCA approaches.

Tools and software that can be used to perform a process-based LCA include BEES[6] by NIST[7], GaBi by thinkstep, GREET by Argonne National Laboratory, MOVES by U.S. environmental protection agency (EPA), PaLATE[8] by University of California, Berkeley, and Pavement LCA by Athena Sustainable Materials Institute.

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[6] Building for Environmental and Economic Sustainability

[7] National Institute of Standards and Technology

[8] Pavement Life-cycle Assessment Tool for Environmental and Economic Effects

Table 5 Selected Recent Studies on Pavement LCA

Author(s) and Year	Subject	Approach
Araujo et al. (2014)	Use phase of asphalt pavement	Process-based
Aurangzeb et al. (2014)	Asphalt mixtures with high RAP content	Hybrid
Butt (2012)	Feedstock energies and asphalt additives	Process-based
Cass and Mukherjee (2010)	HMA and concrete pavement rehabilitation	EIO LCA
Cass and Mukherjee (2011)	Concrete pavement rehabilitation	Hybrid
Chehovits and Galehouse (2010)	Pavement preservation treatments	Process-based
Gangaram (2014)	Pavement preservation treatments	Process-based
Giustozzi et al. (2012)	Preventive maintenance treatments	Process-based
Inti et al. (2016)	Pavement design selection	Process-based
Liu et al. (2014)	Life cycle emissions of pavement design	Hybrid
Loijos et al. (2010)	Pavement environmental impacts	Process-based
Santero (2009)	Pavement environmental impacts	Hybrid
Santos et al. (2014)	Pavement in-place recycling	Process-based
Mack et al. (2014)	Pavement construction and rehabilitation	Process-based
Wang (2013)	Use phase of pavement	Process-based
Zapata and Gambatese (2005)	Asphalt pavement and CRCP[9]	Hybrid
Zhang et al. (2010)	HMA and ECC[10] overlays	Process-based
Salem (2014)	Pavement preservation treatments	Process-based

2.4.2 Life Cycle Cost Analysis

While environmental impacts of roadway MRR projects can be evaluated through life cycle assessment, the economic and social impacts are usually captured by performing a life cycle cost analysis (LCCA). Research by Zhang (2009) and Inti (2016) also incorporated environmental impacts in LCCA by assigning monetary values to elements like greenhouse gas emissions and air and/or water pollution.

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[9] Continuously reinforced concrete pavement

[10] Engineered cementitious composites

Economic and social impact items frequently covered in an LCCA of roadway infrastructure include agency costs (materials, labor, equipment ownership and operation, and transportation), user costs (travel delay costs, fuel costs, and safety costs incurred by driving through a work zone or taking a detour), and relevant community costs. Existing literature reports that user costs are dominated by travel delay costs (Zhang 2009). It should also be noted that not all cost items are applicable to all projects, as certain user costs are only considered in more densely populated states or urban areas. In addition, monetizing social impacts such as noise and local development can be challenging, making it difficult for state DOTs to include these items in their decision-making.

3 METHODOLOGY

As previously shown in Figure 1, the decision support framework proposed in this work for project-level roadway infrastructure management consists of flowcharts and MCDM models for preliminary decision-making, followed by LCA-LCCA models for further quantification of economic, social, and environmental impacts of project alternatives.

3.1 Decision Flowcharts

Determination of candidate alternatives is made through a decision flowchart integrating decision trees and matrices from multiple state departments of transportation (DOTs) with the addition of selected non-traditional techniques. Users start with the targeted roadway distresses and navigate through the flowchart to reach recommended MRR techniques to be used by answering questions regarding distress severity, existence of concurring distresses, technological requirements, and contractor availability. The outputs of decision flowcharts are applicable techniques based on the project requirement, and will serve as input to the MCDM model for the identification of the most appropriate technique. For some public agencies, there may be existing decision flowcharts, trees, or matrices that are well-defined and up-to-date. In this case, users can utilize their own tools instead as long as non-traditional and/or accelerated techniques are taken into consideration.

3.2 Multi-Criteria Decision-Making Model

Multi-criteria decision-making (MCDM) methods are used to evaluate the candidate techniques under a total of twelve criteria. The weights of these criteria are obtained from results of a survey to state DOTs across the United States conducted by Salman et al. (2017). In the survey, attached in Appendix I, major factors affecting the decision-making process on whether to use innovative

MRR techniques or not have been identified and ranked based on their relative importance. Ratings of these factors from over 30 state DOTs serve as major inputs to the three weighting schemes in the MCDM model, following the analytical hierarchy process (AHP), analytical network process (ANP), and user's judgment, respectively. These three weighting schemes are used in evaluating alternatives in a pairwise manner.

The outputs of the MCDM model regarding recommended MRR techniques are twofold. If one of the candidate techniques stands out as the most appropriate with the highest scores among all candidates under all three weighting schemes, decisions can be made by choosing this technique as the project alternative. However, if no conclusion can be made because of the existence of contradicting results among the three weighting schemes or other circumstances, further information is needed to identify the most appropriate technique and the evaluation is escalated to the LCA-LCCA model for quantifying the economic, social, and environmental impact. Depending on the user's preference, project alternative evaluation can be performed through the LCA-LCCA model directly if sufficient data is available.

3.3 LCA-LCCA Model

In the LCA-LCCA model, a total of eight project alternatives with a life cycle of 60 years are generated based on available data including design guidelines, state-of-the-practice specifications and contractor suggestions, with six for flexible pavement and two for rigid pavement. Each alternative features a combination of maintenance, repair, and rehabilitation activities taking place at different years, reflecting the actual scenario where roadway sections experience routine maintenance a short period of time after initial construction, minor repair once deficiencies develop, and major rehabilitation or, eventually, reconstruction when pavement distresses become more severe. The analysis of these project alternatives are conducted by integrating life-cycle assessment (LCA) for evaluation of environmental impacts and life-cycle cost analysis (LCCA) for quantification of economic and social impacts to create holistic comparisons among qualified traditional and/or non-traditional alternatives and make informed project-level decisions.

Conventionally the scope of life cycle assessment (LCA) for civil infrastructure includes material extraction, transportation, construction, use, maintenance, repair, rehabilitation, removal, recycling, and disposal (Loijos 2011). However, in this research on modeling various roadway MRR techniques, many phases within this comprehensive scope are identical across different project-level alternatives such as the construction and use phases. It is also assumed that the roadway will provide similar performance after each rehabilitation activity no matter what technique is used, except that some techniques offer higher levels of service life extension. Therefore, based on the objectives of this research, a comparative life cycle assessment and life cycle cost analysis that focuses on the additional impacts caused by executing MRR processes, both from agency and user perspectives, will sufficiently quantify the difference in overall impacts of project alternatives so that informed decisions can be made. Inclusion of road use phases before and after MRR activities is not necessary.

Existing LCA and LCCA tools and databases applicable to roadway infrastructure maintenance, repair, and rehabilitation have been reviewed and investigated for suitability of the research. As a result, GREET®, Motor Vehicle Emission Simulator (MOVES), and Athena Pavement LCA are used for life cycle assessment while survey results by Salman et al. (2017), RSMeans and other miscellaneous sources are used for life cycle cost analysis, respectively.

Athena Pavement LCA has been selected for this study due to the following reasons:

- It comprehensively covers all aspects in MRR activities in this study including materials, transportation, and equipment;
- It has a material and equipment database that is relatively up-to-date based on industrial average data; and
- It allows modeling of a good number of MRR techniques and customization of materials and processes to analyze user-specified construction procedures.

Similarly, MOVES software is selected for estimating user environmental impacts while the work zone is present due to MRR projects because it has up-to-date localized data regarding traffic distribution, fuel supply and usage, and environmental information at county level. The GREET® database is used to evaluate the environmental impacts of fuels before being consumed by vehicles, which, combined with results of MOVES, provides life cycle user environmental impacts. RSMeans is selected for agency life cycle cost analysis because of data timeliness and comprehensiveness.

To further elaborate on the LCA-LCCA model, a case study based on an interstate highway section in New York State is developed and the overall life cycle impacts are calculated for the eight project alternatives. The customization potential of the LCA-LCCA model is demonstrated through two examples of the what-if scenario analysis of accelerated methods.

4 DECISION FLOWCHARTS AND MCDM MODEL

As explained in Chapter 1, the first phase of developing a decision support system for roadway infrastructure management aims at determining appropriate MRR techniques based on specific roadway deficiencies that the project is attempting to address. In this phase, two decision flowcharts are proposed to shortlist applicable MRR candidates, one for flexible pavements and the other for rigid pavements. Then a multi-criteria decision-making (MCDM) modeling tool is developed to evaluate alternative MRR techniques and provide recommendations for the most appropriate technique based on twelve criteria.

4.1 Decision Flowcharts

Considering that the existing tools tend to include only traditional MRR techniques, decision flowcharts covering a higher number of MRR techniques have been developed for flexible pavements and rigid pavements, respectively (Figures 6 and 7).

The proposed flowcharts are derived from decision trees and decision matrices used by state DOTs and industry best practices. Although these decision trees and matrices vary greatly from one to another, they either form the relationship between the causes of pavement distresses and MRR strategies, or define threshold values of pavement performance indicators (e.g. Ride Quality Index, RQI) to make MRR recommendations. Some tools also indicate the levels of effectiveness (e.g. High, Medium, Low, and Not Applicable) of potential MRR alternatives for each type of distress. Due to the fact that existing decision trees and matrices are mostly developed in the 2000s or earlier and there is certain degree of disagreement among them, two new decision flowcharts that cover a higher number of MRR alternatives are proposed.

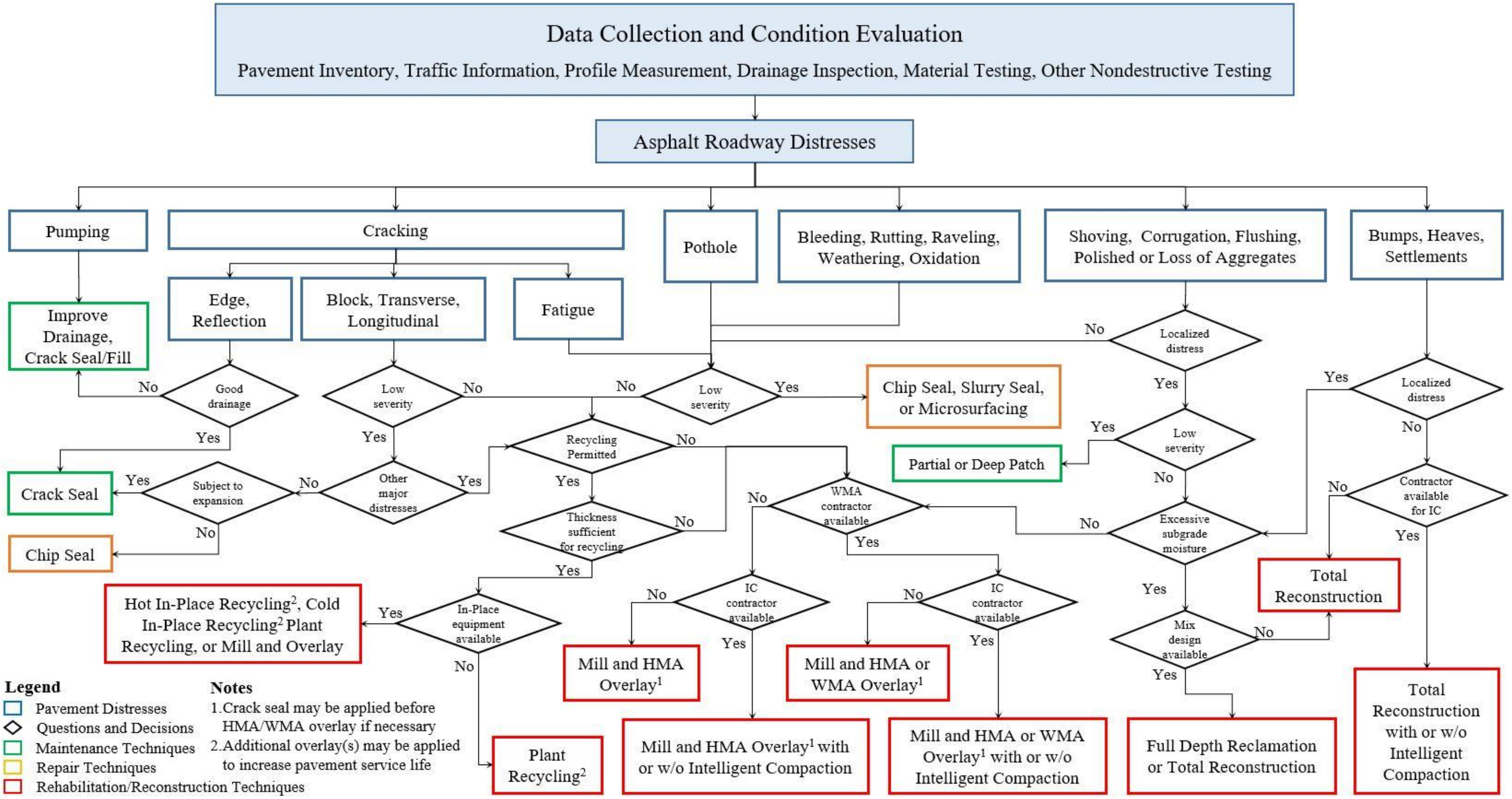
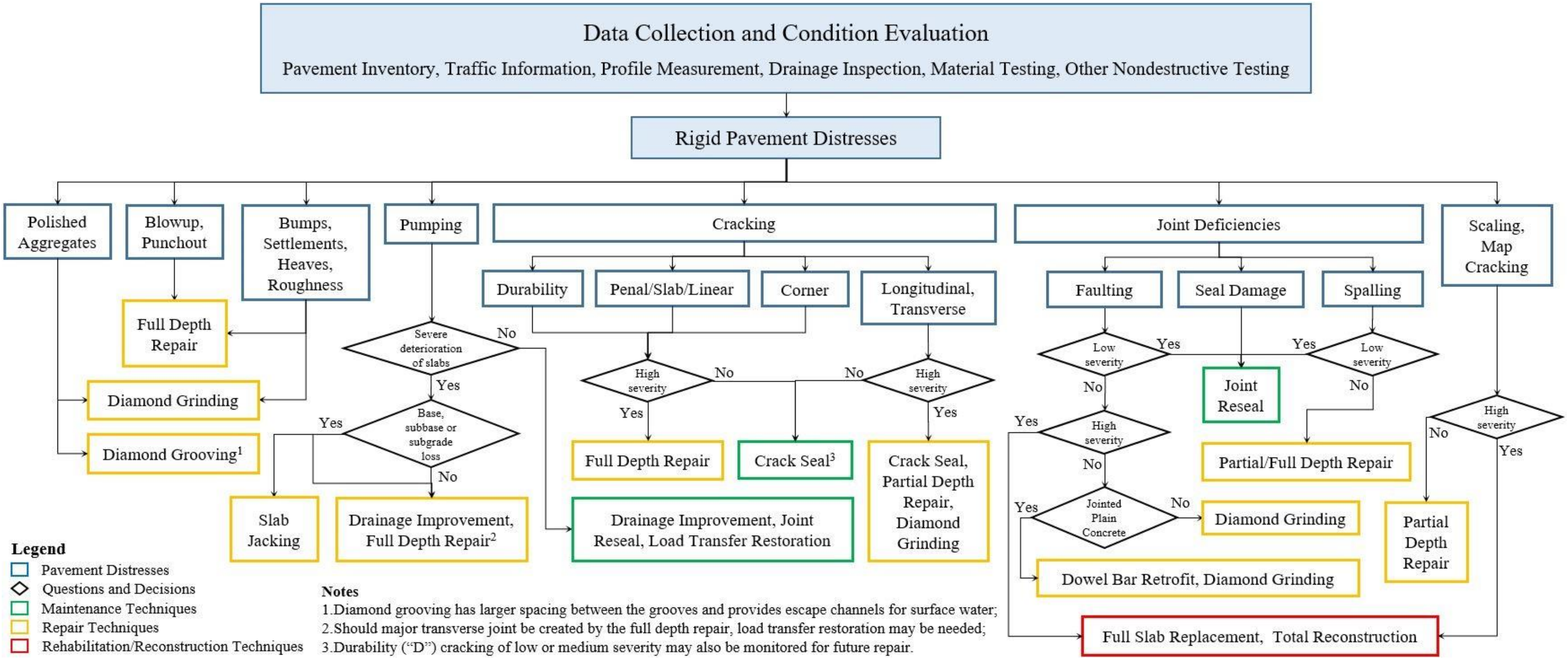


Figure 6 MRR Technique Selection Flowchart for Flexible Pavement

Adapted from Hall et al. (2001), NYSDOT (1999), Hicks et al. (2000), Moulthrop et al. (1999), Hunt (1991), and Jahren et al. (1999)



Notes

1.Diamond grooving has larger spacing between the grooves and provides escape channels for surface water;

2.Should major transverse joint be created by the full depth repair, load transfer restoration may be needed;

3.Durability ("D") cracking of low or medium severity may also be monitored for future repair.

Figure 7 MRR Technique Selection Flowchart for Rigid Pavement

Adapted from Hall et al. (2001), NYSDOT (1999), SDDOT (2010), NCPP (2004), Caltrans Division of Maintenance (2008).

Determination of appropriate MRR techniques is performed by answering several descriptive questions and concluding on one or more techniques that are suitable for addressing the specific pavement distresses. Should the answers for any questions be unclear, it is recommended that all potentially applicable techniques be included in the next step of analysis using multi-criteria decision-making methods.

4.2 Multi-Criteria Decision-making Model

Salman et al. (2017) have conducted a study on the state of practice for the innovative MRR techniques of asphalt pavements, where a ten-question survey was distributed to state DOT officials and state representatives of FHWA. In one of the questions, highway management agencies were asked to rank a number of factors based on their respective importance for the decision-making process on whether innovative techniques in general should be utilized. Survey responses collected from 31 individuals are summarized in Table 6.

Table 6 Survey Results on Factors Affecting Decision-making of Innovative MRR Techniques by Salman et al. (2017)

Factors Affecting Decision-Making	Average Ratings*	Standard Deviation
Condition of the Existing Road	4.16	1.16
Construction GHG Emissions	2.03	1.05
Construction Schedule	3.26	0.86
Contractor Availability**	4.33	0.58
Initial Construction Costs	4.23	1.02
Lane Closures	3.61	1.02
Life Cycle Costs	4.10	0.98
Technical Reliability**	4.00	0.00
Traffic Delays	3.68	1.01
User Fuel Consumption	1.84	1.07
User GHG Emissions	1.84	1.04
Virgin Materials Used	2.94	0.89

* Ratings are on a scale of 1 to 5 with 1 being the least important and 5 being the most important
**Factors specified by survey respondents under the “other” category in the questionnaire

Based on the nature of the problem and survey responses, proper multi-criteria decision-making (MCDM) methods are needed to determine the priorities for each factor so that applicable roadway MRR techniques obtained from the decision flowcharts can be analyzed and the most appropriate technique(s) can be identified. It is noteworthy that although the survey by Salman et al. (2017) targets on innovative MRR techniques for asphalt/flexible pavements, factors affecting decision-making procedures identified in the survey are deemed to apply to both flexible and rigid pavements.

4.2.1 Analytical Hierarchy Process

Following the procedures of Analytical Hierarchy Process (AHP), the pairwise comparison matrix are developed to calculate the relative importance of factors between one another (See Table 7), where:

$$a_{ij} = \frac{Rating\ of\ Factor\ i}{Rating\ of\ Factor\ j} \tag{1}$$

Table 7 AHP Pairwise Comparison Matrix of Factors

Pairwise Comparison Matrix	CER	CGE	CS	CA	ICC	LC	LCC	TR	TD	UFC	UGE	VMU
Condition of the Existing Road	1	2.048	1.277	0.960	0.985	1.152	1.016	1.040	1.132	2.263	2.263	1.418
Construction GHG Emissions	0.488	1	0.624	0.469	0.481	0.563	0.496	0.508	0.553	1.105	1.105	0.692
Construction Schedule	0.783	1.603	1	0.752	0.771	0.902	0.795	0.815	0.886	1.772	1.772	1.110
Contractor Availability	1.041	2.132	1.330	1	1.025	1.199	1.058	1.083	1.178	2.357	2.357	1.476
Initial Construction Costs	1.016	2.079	1.297	0.975	1	1.170	1.031	1.056	1.149	2.298	2.298	1.440
Lane Closures	0.868	1.778	1.109	0.834	0.855	1	0.882	0.903	0.982	1.965	1.965	1.231
Life Cycle Costs	0.984	2.016	1.257	0.945	0.969	1.134	1	1.024	1.114	2.228	2.228	1.396
Technical Reliability	0.961	1.968	1.228	0.923	0.947	1.107	0.976	1	1.088	2.175	2.175	1.363
Traffic Delays	0.884	1.810	1.129	0.849	0.870	1.018	0.898	0.919	1	2.000	2.000	1.253
User Fuel Consumption	0.442	0.905	0.564	0.424	0.435	0.509	0.449	0.460	0.500	1	1.000	0.626
User GHG Emissions	0.442	0.905	0.564	0.424	0.435	0.509	0.449	0.460	0.500	1.000	1	0.626
Virgin Materials Used	0.705	1.444	0.901	0.677	0.695	0.813	0.717	0.734	0.798	1.596	1.596	1

In a classic AHP, a hierarchical structure consists of criteria and sub-criteria. Analysis is conducted in a "top-down" manner with multiple iterations of evaluation. In this research, however, in order to avoid complication during the survey process, all factors listed are treated as criteria for analysis. As a result, the pairwise comparison matrix of criteria is constructed at a single level instead of multiple levels. Following the algorithms of AHP, normalized priorities for all factors reflecting their respective importance are obtained through the weighted pairwise comparison matrix and are shown in Table 8.

Table 8 Normalized Priorities of Factors

Factors Affecting Decision-Making	**Abbr.**	**Estimated Weights**
Condition of the Existing Road	CER	0.104
Construction GHG Emissions	CGE	0.051
Construction Schedule	CS	0.081
Contractor Availability	CA	0.108
Initial Construction Costs	ICC	0.106
Lane Closures	LC	0.090
Life Cycle Costs	LCC	0.102
Technical Reliability	TR	0.100
Traffic Delays	TD	0.092
User Fuel Consumption	UFC	0.046
User GHG Emissions	UGE	0.046
Virgin Materials Used	VMU	0.073

An important assumption of AHP method is that elements in the hierarchical structure are independent from each other on the same level and from those on lower levels; only elements at higher level (e.g. criteria) have influence on those at lower level (e.g. sub-criteria). Meanwhile, however, considering the nature of decision-making associated with using MRR techniques, the factors identified and investigated in the survey have various degrees of interdependency. For example, User Fuel Consumption has a major impact on User Greenhouse gas Emission, and Traffic Delays are heavily affected by Lane Closures. Should these interdependencies be ignored in MCDM analysis, the final outcomes would be less accurate, and the recommendation of most appropriate techniques would be less practically beneficial. Therefore, in order to take into consideration the interdependencies among factors, the Analytical Network Process (ANP) method is also adopted for the MCDM analysis in this study.

4.2.2 Analytical Network Process

In this research, interdependencies between twelve factors are categorized into four levels based on magnitude of influence. A pairwise influence matrix is proposed based on common understanding of interrelationship between factors, as shown in Table 9. Each cell in the matrix shows the magnitude of influence from the factor in the corresponding row (on the left) on the factor in the corresponding column (on the top). For a pair of factors, denoted as A and B, the magnitude of influence from A on B may not be the same as that from B on A. One example is the relationship between Condition of Existing Road and Initial Construction Cost —— the former factor has a strong influence on the latter, but the latter does not have discernible impact on the former.

In the ANP algorithm, interdependencies of elements are modeled by comparing the levels of influence for two elements on a control element. Based on the magnitude of influence categorization in Table 9, to generate ratings of inter-factor influence that can be utilized by ANP, Table 10 is developed using a similar ratio scale to conventional AHP/ANP paradigm. For each factor as a control criterion, two other factors are compared and the relative importance is determined and fed into an interdependency pairwise comparison matrix, resulting in a total of twelve interdependency pairwise comparison matrices. Table 11 shows an example of such a matrix for the factor of Construction Schedule.

Table 9 ANP Pairwise Influence Matrix of Factors

Pairwise Influence Matrix		Influence on											
		CER	CGE	CS	CA	ICC	LC	LCC	TR	TD	UFC	UGE	VMU
Influence from	CER		W	S	N	S	W	W	N	W	N	N	W
	CGE	N		N	N	N	N	W	N	N	N	N	N
	CS	N	S		N	S	S	W	N	W	W	W	N
	CA	N	W	S		S	W	S	W	W	N	N	S
	ICC	N	N	W	N		N	S	N	N	N	N	W
	LC	N	N	S	N	W		W	N	S	S	W	N
	LCC	N	N	W	N	W	N		N	N	N	N	N
	TR	N	W	W	S	W	W	S		W	N	N	W
	TD	N	N	N	N	N	N	W	N		V	S	N
	UFC	N	N	N	N	N	N	S	N	N		V	N
	UGE	N	N	N	N	N	N	S	N	N	N		N
	VMU	N	S	W	N	S	N	W	N	N	N	N	

Notes: V- Very Strong Influence; S- Strong Influence; W- Weak Influence; N- Negligible Influence

Table 10 Pairwise Comparison Ratings of Inter-Factor Influence

Pairwise Comparison Rating of Inter-Factor Influence					
On Factor *i*		Influence from Factor *k*			
		Very Strong	Strong	Weak	Negligible
Influence from Factor *j*	Very Strong	1	3	5	7
	Strong	1/3	1	3	5
	Weak	1/5	1/3	1	3
	Negligible	1/7	1/5	1/3	1

The eigenvector of the interdependency pairwise comparison matrix serves as an input to the ANP supermatrix including the overall goal, all twelve criteria, and relative importance ratings of influence from two other criteria on this criterion. A publicly accessible software program, Super Decision, is used to perform ANP calculations. In Super Decision, the pairwise comparison of inter-factor influence is presented in multiple ways including graphical, verbal, matrix, questionnaire, and direct. Instead of reciprocals, the ratings of pairwise inter-factor influence are presented by the same value with colorific distinction, as shown in Table 12. The unweighted supermatrix of factors in Super Decision is presented in Table 13.

Table 11 Interdependency Pairwise Comparison Matrix for Construction Schedule

Interdependency Pairwise Comparison Matrix												
Control: Construction Schedule		CER	CGE	CA	ICC	LC	LCC	TR	TD	UFC	UGE	VMU
		S	N	S	W	S	W	W	N	N	N	W
CER	S	1	5	1	3	1	3	3	5	5	5	3
CGE	N	1/5	1	1/5	1/3	1/5	1/3	1/3	1	1	1	1/3
CS	S	1	5	1	3	1	3	3	5	5	5	3
CA	W	1/3	3	1/3	1	1/3	1	1	3	3	3	1
ICC	S	1	5	1	3	1	3	3	5	5	5	3
LC	W	1/3	3	1/3	1	1/3	1	1	3	3	3	1
LCC	W	1/3	3	1/3	1	1/3	1	1	3	3	3	1
TR	N	1/5	1	1/5	1/3	1/5	1/3	1/3	1	1	1	1/3
TD	N	1/5	1	1/5	1/3	1/5	1/3	1/3	1	1	1	1/3
UFC	N	1/5	1	1/5	1/3	1/5	1/3	1/3	1	1	1	1/3
UGE	W	1/3	3	1/3	1	1/3	1	1	3	3	3	1

Table 12 Pairwise Comparison Ratings of Inter-Factor Influence

Pairwise Comparison Rating of Inter-Factor Influence					
On Factor *i*		Influence from Factor *k*			
		Very Strong	Strong	Weak	Negligible
Influence from Factor *j*	Very Strong	1	3	5	7
	Strong	3	1	3	5
	Weak	5	3	1	3
	Negligible	7	5	3	1

With interdependencies of factors taken into consideration, priorities of the twelve factors using ANP algorithm are then calculated in Super Decision. Results are compared against priorities by AHP in Table 14. It is observed that in ANP, higher emphasis has been placed on factors with more profound impact on their peers (e.g. Condition of the Existing Road and Construction Schedule), while factors that are heavily influenced by others (e.g. Life Cycle Costs and User GHG Emissions) receive lower priorities.

Table 13 Unweighted Supermatrix in ANP

SUPER MATRIX	CER	CGE	CS	CA	ICC	LC	LCC	TR	TD	UFC	UGE	VMU	Goal
CER	0	0.104	0.189	0.067	0.169	0.132	0.048	0.077	0.120	0.041	0.037	0.132	0.104
CGE	0.091	0	0.030	0.067	0.029	0.046	0.048	0.077	0.042	0.041	0.037	0.046	0.051
CS	0.091	0.229	0	0.067	0.169	0.279	0.048	0.077	0.120	0.112	0.100	0.046	0.081
CA	0.091	0.104	0.189	0	0.169	0.132	0.143	0.231	0.120	0.041	0.037	0.279	0.108
ICC	0.091	0.383	0.078	0.067	0	0.046	0.143	0.077	0.042	0.041	0.037	0.132	0.106
LC	0.091	0.383	0.189	0.067	0.070	0	0.048	0.077	0.268	0.209	0.100	0.046	0.090
LCC	0.091	0.383	0.078	0.067	0.070	0.046	0	0.077	0.042	0.041	0.037	0.046	0.102
TR	0.091	0.104	0.078	0.333	0.070	0.132	0.143	0	0.120	0.041	0.037	0.132	0.100
TD	0.091	0.383	0.030	0.067	0.029	0.046	0.048	0.077	0	0.347	0.199	0.046	0.092
UFC	0.091	0.383	0.030	0.067	0.029	0.046	0.143	0.077	0.042	0	0.338	0.046	0.046
UGE	0.091	0.383	0.030	0.067	0.029	0.046	0.143	0.077	0.042	0.041	0	0.046	0.046
VMU	0.091	0.229	0.078	0.067	0.169	0.046	0.048	0.077	0.042	0.041	0.037	0	0.073
Goal	0	0	0	0	0	0	0	0	0	0	0	0	1

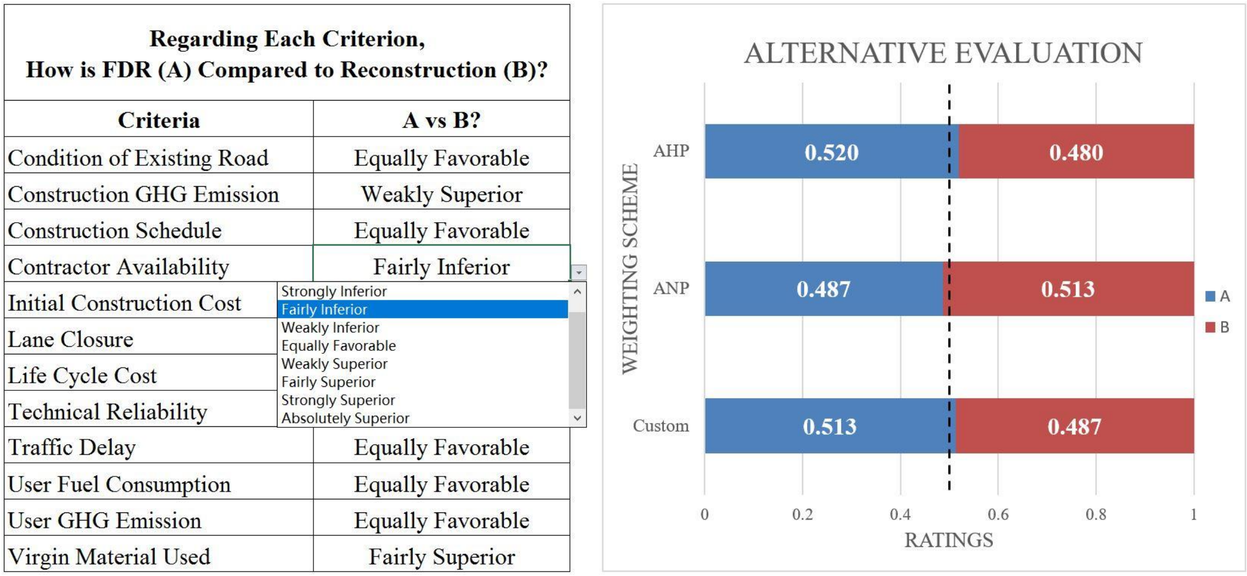
Table 14 Priorities of Factors in ANP and AHP

Factors Affecting Decision-Making	**Priorities**	
	ANP	**AHP**
Condition of Existing Road	0.094	0.104
Construction GHG Emission	0.050	0.051
Construction Schedule	0.106	0.081
Contractor Availability	0.128	0.108
Initial Construction Cost	0.067	0.106
Lane Closure	0.101	0.090
Life Cycle Cost	0.057	0.102
Technical Reliability	0.115	0.100
Traffic Delay	0.080	0.092
User Fuel Consumption	0.072	0.046
User GHG Emission	0.056	0.046
Virgin Material Used	0.073	0.073

4.2.3 Multi-Criteria Decision-Making Modeling Tool

Considering the ease of use and capability of user customization, a multi-criteria decision-making (MCDM) modeling tool in the form of an Excel file using AHP/ANP methods is developed to perform project-specific analysis to identify most appropriate alternatives. The

MCDM modeling tool integrates AHP calculation procedures, visual displays of pairwise comparison results, and drop-down menu options for the selection of relative importance descriptions. It also allows generating outputs based on user-defined custom weights for factors (the default user-defined weights are ratings provided by NYSDOT from the survey).



Regarding Each Criterion,
How is FDR (A) Compared to Reconstruction (B)?

Criteria	A vs B?
Condition of Existing Road	Equally Favorable
Construction GHG Emission	Weakly Superior
Construction Schedule	Equally Favorable
Contractor Availability	Fairly Inferior
Initial Construction Cost	
Lane Closure	
Life Cycle Cost	
Technical Reliability	
Traffic Delay	Equally Favorable
User Fuel Consumption	Equally Favorable
User GHG Emission	Equally Favorable
Virgin Material Used	Fairly Superior

Figure 8 MCDM Modeling Tool “Evaluation” Interface

The MCDM tool in the Excel file consists of Introduction”, “Evaluation”, “Factors”, and “Matrices” sheets. In the “Evaluation” sheet, users may use the drop-down menu on the left side to determine the relative importance of two alternatives regarding each criterion, as shown in Figure 8. Ratings of the two alternatives using AHP priorities, ANP priorities, and custom priorities will then be calculated and shown in the bar chart on the right of the same sheet. The higher ratings one alternative receives, the more preferable it is compared to its counterpart. The “Factors” sheet contains the weights based on the survey results calculated through AHP and ANP, and users can apply their custom weights in the last column. The “Matrices” sheet contains equations and values used in calculations. Table 15 provides values corresponding to the various relative importance categories on a scale of 1 to 9 following the classic AHP scale.

Table 15 Pairwise Comparison Rating Scheme

Pairwise Comparison Rating Scheme	
Evaluation	**Rating**
Absolutely Inferior	1/9
Strongly Inferior	1/7
Fairly Inferior	1/5
Weakly Inferior	1/3
Equally Favorable	1
Weakly Superior	3
Fairly Superior	5
Strongly Superior	7
Absolutely Superior	9

In the hypothetical case in Figure 8, the overall ratings for the two alternatives are relatively close. In addition, contradicting results are generated, as two out of the three outputs indicate that Alternative A is more favorable while the third outputs advocates Alternative B. Therefore, further analysis is needed to determine which alternative is more appropriate.

4.2.4 Demonstration Case Studies

Two asphalt pavement MRR projects in Onondaga County, New York, are selected from Pavement Data Reports (NYSDOT 2012; NYSDOT 2015) to demonstrate the use of proposed MCDM tool. The first case study compares milling and overlay technique with cold in-place recycling (CIR) method, and the second case study evaluates full depth reclamation (FDR) and total reconstruction. The level of agreement between the recommendations by the MCDM tool and the actual techniques utilized by NYSDOT is examined. It should be noted that in the State of New York, the decision to use warm mix asphalt (WMA) is generally left to the discretion of the contractor. In addition, innovative compaction (IC) has been implemented only in pilot projects. Therefore, documentation on projects involving these two techniques was limited.

4.2.4.1 I-81 JCT Colvin ST Pavement Rehabilitation Project

I-81 JCT Colvin St Pavement Rehabilitation Project was undertaken in 2012 with an objective to address isolated alligator (fatigue) cracking with low-severity rutting and bumps. The rehabilitated highway was a six-lane, 0.46 mile roadway segment of urban principal arterial interstate with an annual average daily traffic (AADT) of 79,504 and a peak-hour v/c ratio of 0.89 at the time of project execution (NYSDOT 2012).

Based on the decision flowchart and the practices of NYSDOT, the two candidate rehabilitation techniques were (A) milling and HMA overlay and (B) cold in-place recycling (CIR). As CIR has been used extensively in the region, it features comparable contractor availability, technical reliability, as well as construction cost to traditional milling and overlay method. Both methods can equally address pavement distresses and require similar traffic management plan of lane closures. However, CIR has slightly shorter construction schedule, resulting in reduced traffic delay, user fuel consumption, and user GHG emissions. CIR also uses fewer virgin materials and generates lower levels of construction GHG emissions. The expected life cycle cost for CIR is also lower than that for milling and overlay.

Figure 9 shows the outputs of the MCDM tool with the information presented above as inputs. All methods have ruled alternative B, CIR, as the recommended technique for this project. This conclusion coincides with the actual course of action followed by NYSDOT (NYSDOT 2012). It is also noteworthy that some of the evaluation results, such as regarding contractor availability and technical reliability, may not apply to projects in other localities where CIR has not yet been frequently practiced, as the improvement of technical reliability largely depends on the prolonged effort by local contractors rather than improvement in the agencies' decision-making processes.

Regarding Each Criterion, How is Milling & Overlay (A) Compared to CIR (B)?

Criteria	A vs B?
Condition of Existing Road	Equally Favorable
Construction GHG Emission	Weakly Inferior
Construction Schedule	Weakly Inferior
Contractor Availability	Equally Favorable
Initial Construction Cost	Equally Favorable
Lane Closure	Equally Favorable
Life Cycle Cost	Weakly Inferior
Technical Reliability	Equally Favorable
Traffic Delay	Weakly Inferior
User Fuel Consumption	Weakly Inferior
User GHG Emission	Weakly Inferior
Virgin Material Used	Fairly Inferior

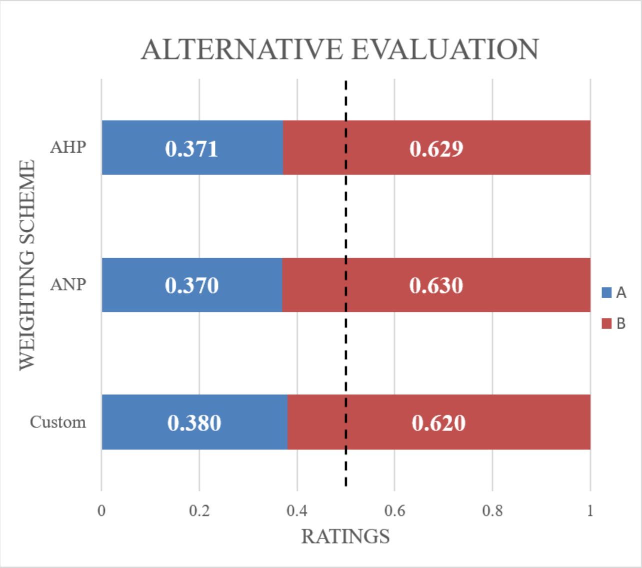


Figure 9 MCDM Modeling Tool Modeling Results for I-81 Project

4.2.4.2 RT11 State St Pavement Rehabilitation Project

This project was completed in 2014 and it aimed to address the general alligator (fatigue) cracking with 19 bumps on a two-lane, 0.26 mile urban roadway segment. This roadway segment had an AADT of 6,802 and a peak-hour v/c ratio of 0.5 in 2015. The subbase was unstabilized (NYSDOT 2015).

Based on the decision flowchart and the practices of NYSDOT, the two candidate rehabilitation techniques were (A) full depth reclamation (FDR) and (B) total reconstruction. Both of these techniques are capable of addressing the distresses encountered on this roadway segment. However, FDR is not included in the NYSDOT Work Type Codes, indicating questionable technical reliability and contractor availability. Regarding initial construction costs, life cycle costs, virgin material used, and construction emissions, FDR has an advantage over conventional total reconstruction. Both techniques feature comparable construction schedules and require similar traffic management plans, resulting in comparable traffic delays. Since this urban local roadway section has relatively low v/c ratio, the difference between the two techniques in terms of impacts on road users, is considered negligible.

Figure 10 shows the outputs of the MCDM tool with the information presented above as inputs. Results using AHP and Custom priorities are in favor of FDR alternative, while the result using ANP priorities advocates total reconstruction. This is because ANP assigns higher weights to technical reliability and contractor availability, and total reconstruction method prevails under these two criteria.

Considering the small difference between the three results and the fact that outputs are not in an agreement, it can be concluded that both techniques are appropriate candidates for this project. Therefore, it is reasonably justified that NYSDOT actually used total reconstruction method for this project (NYSDOT 2015).

Regarding Each Criterion, How is FDR (A) Compared to Reconstruction (B)?	
Criteria	**A vs B?**
Condition of Existing Road	Equally Favorable
Construction GHG Emission	Weakly Superior
Construction Schedule	Equally Favorable
Contractor Availability	Fairly Inferior
Initial Construction Cost	Weakly Superior
Lane Closure	Equally Favorable
Life Cycle Cost	Weakly Superior
Technical Reliability	Fairly Inferior
Traffic Delay	Equally Favorable
User Fuel Consumption	Equally Favorable
User GHG Emission	Equally Favorable
Virgin Material Used	Weakly Superior

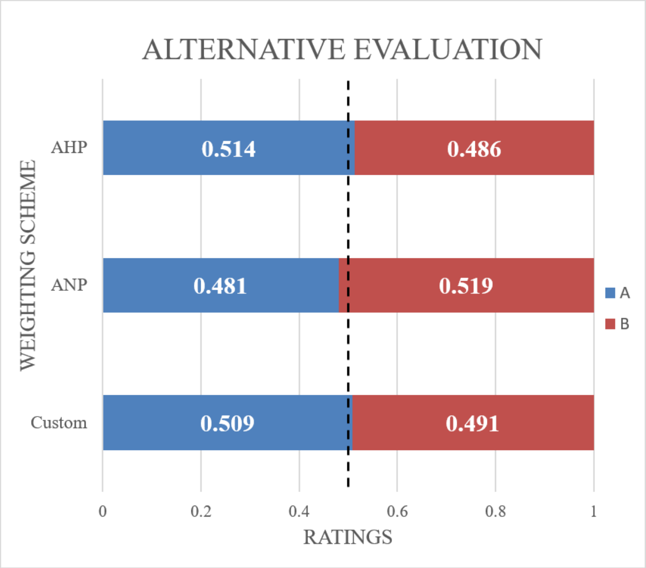


Figure 10 MCDM Modeling Tool Modeling Results for RT11 Project

5 LCA-LCCA MODEL

The LCA-LCCA model identifies the life cycle economic, social, and environmental impacts of project alternatives using traditional and non-traditional MRR techniques to provide decision makers with quantitative justification of alternative selection.

5.1 Formulation of Project Alternatives

5.1.1 Demonstration Roadway Geometry

To comprehensively identify the life cycle economic, social, and environmental impacts of different MRR techniques (both traditional and non-traditional), a demonstration road section is created according to NYSDOT specifications and practices, and a number of project-level alternatives are developed to reflect different MRR strategies over the life cycle.

The demonstration road section is a one-mile long single-bound two-lane interstate highway with paved shoulders on both sides. Separate sections are created for flexible pavements and rigid pavements with the same geometric features. An Interstate section is selected because Interstates support most ground freight transport and are therefore crucial to the nation’s economy and well-being, and their MRR activities are most labor and material intensive, resulting in the largest overall life cycle impacts.

The lane width is 12 feet, along with shoulders of 6 feet wide on both sides. Materials for flexible pavement are HMA PG-70-62 for wearing course of 2” in thickness, HMA PG-64-22 for binder and base course of 2” and 6” in thickness, respectively, and granular stone for subbase of 12” in thickness. Materials for rigid pavement are concrete benchmark 4000 psi for PCC course of 10” in thickness and granular stone for subbase of 12” in thickness. Figure 11 shows the courses and overall composition of flexible and rigid pavement. It should be noted that the figure is not drawn to scale.

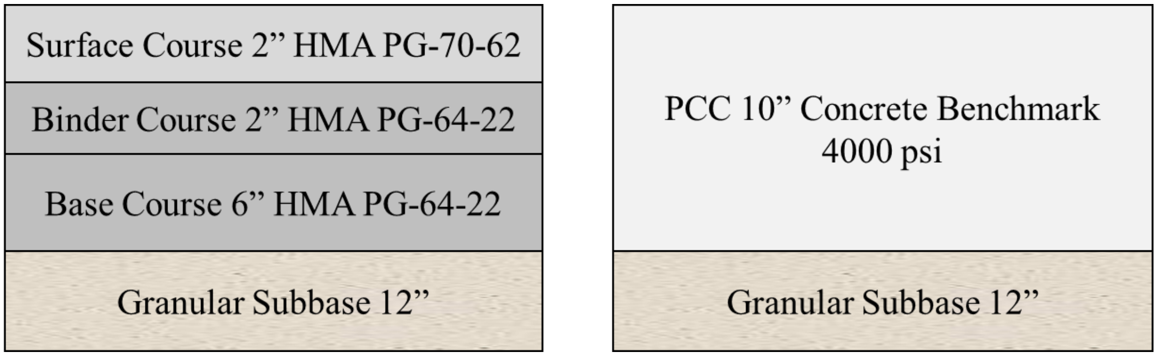


Figure 11 Demonstration roadway pavement geometry: Flexible (left) and Rigid (right)

5.1.2 MRR Activities

It is generally acknowledged that a newly built pavement section will experience cycles of maintenance, repair, and rehabilitation activities before it is eventually reconstructed. For roadways with flexible pavements, a typical cycle starts with maintenance actions such as crack sealing, continues with repair actions such as patching, and ends with rehabilitation actions. If all MRR activities are being performed properly and there are no structural deficiencies in subbase and subgrade courses, the pavement section can be "perpetual". For roadways with rigid pavements, a typical cycle consists of maintenance actions such as joint sealing, and repair or rehabilitation actions such as partial or full depth repair and diamond grinding.

In this research, major parameters that differentiate project-level alternatives are (1) the MRR activities to be performed, (2) the scope and quantities of these activities, and (3) the timing of these activities. Tables 16 and 17 summarize the characteristics of all MRR activities considered in this research for flexible pavement roadways and rigid pavement roadways, respectively. Other MRR activities that apply to composite pavements (e.g. asphalt overlays applied to concrete pavements) are not taken into consideration due to high complexity.

Table 16 MRR Activities and Characteristics for Roadways with Flexible Pavement

MRR Category	Activities	Quantities and Specifications	Estimated Service Life (Years)	Activity Duration per lane (Days)
Maintenance	Crack Seal	3/8" wide 1" depth, 1000ft /ln	3	1
		3/8" wide 1" depth, 1500ft / ln	3	1
		3/8" wide 1" depth, 3750ft / ln	4	3
		3/8" wide 1" depth, 4500ft / ln	4	3
Repair	Patch	2% lane area, 3 inch deep	8	3
		3% lane area, 3 inch deep	8	5
Rehabilitation	Mill and HMA or WMA Fill	4"(2" binder + 2" wearing)	15	37
		2" wearing course, no shoulder	9	15
	Hot In-Place Recycling (HIPR)	Recycle 4" + 2" HMA wearing course	15	16
	Cold In-Place Recycling (CIR)	Recycle 4"+ 2" HMA wearing course	15	16
	Full Depth Reclamation (FDR)	Recycle 6" (2" for wearing, binder & base) + 2" HMA wearing course	18	21
	Mill and HMA Fill with Intelligent Compaction (IC)	4" Paving	17	37
		2" Paving, no shoulder	10	15

Table 17 MRR Activities and Characteristics for Roadways with Rigid Pavement

MRR Category	Activities	Quantities and Specifications	Estimated Service Life in Years	Activity Duration per lane in Days
Maintenance	Concrete Joint Seal	4400 ft/ln-mile	13	2
		6600 ft/ln-mile	15	2
Repair and Rehabilitation	Concrete Partial Depth Repair	2% lane area	13	8
		5% lane area	15	13
	Concrete Full Depth Repair	10% lane area	15	15
		15% lane area	15	20
	Concrete Full Depth Repair using Precast Concrete Slabs	10% lane area	15	4
		15% lane area	15	6
	Diamond Grinding	Grind 0.2 inch off 100% lane area	15	4

The estimated service life values for Mill and HMA/WMA Fill, HIPR, CIR, and FDR are obtained from the survey by Salman et al. (2017), while the rest of the estimated service life values and quantities and specifications of each activity are obtained from Athena Pavement

LCA databases. The duration per lane for each activity is calculated based on the default production rates in RSMeans, published production rates from FHWA and State DOT (for concrete full depth repair with precast concrete slabs), and recommended curing days by NYSDOT when curing is needed. Actual activities may take twice as long since the roadway section has two lanes per direction.

5.1.3 Rehabilitation Schedules

The estimated service life of each MRR activity is a key input in developing a 60-year rehabilitation schedule of each project-level alternative. A total of six alternatives, labeled “Traditional”, “Recycling”, “WMA”, “CIR”, “FDR”, and “IC”, are generated for flexible pavements, and two other alternatives, labeled “CIP” and “PCP”, are generated for rigid pavements. Table 18 shows the example of rehabilitation schedule for alternative “Traditional”, where Mill and HMA Fill technique is used as the rehabilitation technique along with other maintenance and repair activities that are constant across different alternatives. The timing of activities is developed so that it reflects the job sequence in reality, where maintenance treatments are applied to the newly rehabilitated roadway, followed by repairs once distresses propagate, and eventually rehabilitations are required when distresses are beyond repair. Due to the difference in nature between asphalt pavements and concrete pavements, the activities involved and their timings are considerably different. Additional rehabilitation schedules can be found in Appendix II.

The following items are worth being highlighted on the development of alternatives:

- Every rehabilitation schedule starts with a major rehabilitation activity at year 0, reflecting the decision made on the technique used for the current project. This is different from the scenario where new construction is performed at the very beginning.

- Moderate rehabilitation activities use mostly traditional method of *Mill and HMA Fill* except for the “WMA” alternative, which uses *Mill and WMA Fill*. The major rehabilitation activities for “CIR” and “FDR” alternatives have adopted non-traditional techniques of CIR and FDR, respectively, because they generally require a minimum pavement thickness of 4” and the major rehabilitation activities apply to both wearing and binder courses.
- As for the “IC” alternative, Tennessee Department of Transportation reported that the claimed benefit of shortened duration had been largely offset by the additional time spent on the learning process to properly apply the IC instruments (Bledsoe 2015). Meanwhile, NYSDOT recognized the color-coding feature in the visual display as the only observed benefit of using IC, which is hardly quantifiable. Additionally, IC instruments either consume a negligible amount of energy compared to the entire paving process (e.g. in the case of GPS), or contribute to the overall energy consumption of rollers (e.g. in the case of accelerometers, infrared temperature sensors, and processing software), which is difficult to differentiate and quantify. As a result, the energy use of IC instruments is also excluded. Therefore, the only difference of the “IC” alternative compared to “Traditional” alternative considered in this research is the additional estimated service life of 1 year for moderate rehabilitation and 2 years for major rehabilitation.
- The analysis period of 60 years is selected to ensure that all alternatives have equal numbers of moderate and major rehabilitation activities, while using 50 years results in fewer major rehabilitation activity for “FDR” and “IC” alternatives, leading to less meaningful results. However, “FDR” and “IC” alternatives do have fewer maintenance and repair activities throughout the entire analysis period.

Table 18 Rehabilitation Schedule using Mill and HMA Fill

Year	Service Life	MRR Activity	Detail
0	15	M&F HMA	4" (2" wearing + 2" binder)
3	3	Crack Seal	1000 ft/ln-mile
6	4	Crack Seal	3750 ft/ln-mile
10	8	Patch	2% lane area
15	9	M&F HMA	2" wearing course, no shoulder
21	8	Patch	3% lane area
24	15	M&F HMA	4" (2" wearing + 2" binder)
27	3	Crack Seal	1500 ft/ln-mile
30	4	Crack Seal	4500 ft/ln-mile
34	8	Patch	2% lane area
39	9	M&F HMA	2" wearing course, no shoulder
45	8	Patch	3% lane area
48	15	M&F HMA	4" (2" wearing + 2" binder)
51	3	Crack Seal	1500 ft/ln-mile
54	4	Crack Seal	4500 ft/ln-mile
58	8	Patch	2% lane area

After all alternatives (six for flexible pavement and two for rigid pavement) are developed, life cycle assessment and life cycle cost analysis are performed to evaluate their impacts following triple bottom line of sustainability, and results are compared to those for other alternatives of the same pavement type.

5.2 Life Cycle Assessment of Environmental Impacts

As discussed before, the scope of LCA in this research only includes the life cycle impacts incurred during the execution of an MRR project, assuming different project alternatives have the same “before” and “after” conditions. Specifically, for public agencies executing MRR activities, emissions and energy use are analyzed during (1) material extraction, processing, and manufacturing, (2) material and equipment transportation, and (3) equipment operations. For road users, it is assumed that execution of MRR activities would require closure of one lane out of two for a certain period of time and would result in traffic congestion, resulting in increased emissions and fuel consumptions. Therefore, additional emissions and energy consumptions compared to normal traffic scenarios are calculated for user life cycle environmental impacts.

5.2.1 Agency Life Cycle Assessment

Using the information of eight project alternatives from previous section as inputs, a life cycle assessment of 60 years is conducted using Athena Pavement LCA software. The transportation distances are derived from 2012 Commodity Flow Survey by Census Bureau and the Bureau of Transportation Statistics (USDOT and USDOC 2015). Relevant data are shown in Table 19.

As asphalt mixtures consist of roughly 5% of bitumen and 95% of aggregates by weight, the calculated average transportation distance of asphalt mixture materials is 33 miles. For materials used for rigid pavement, concrete mixtures have 16% of Portland cement, 37% of sand, and 41% of stone aggregate with the rest being water. Therefore the calculated average shipment distance is 44 miles. The average distance from site to stockpile is assumed to be 10 miles for all alternatives.

Table 19 Transportation Data from CFS 2012

SCTG Code	Commodity	Average per shipment in mile
110	Sand	51
120	Gravel and crushed stone	30
199	Other products of petroleum refining, and coal products,	83
311	Portland cement	86
345	Material handling, excavating, boring, and related machinery and equipment	422

Due to the fact that Athena Pavement LCA software does not feature use of precast concrete pavement as one of the rehabilitation options and that the material and equipment database is encrypted for security purposes, an approximation approach is used to model “PCP” alternative. It is assumed that “CIP” and “PCP” alternatives use the same amount of concrete for full depth repair of distressed pavement sections. Considering that the major equipment for “PCP” is truck-mounted crane for transporting, lifting, and placing precast concrete slabs, whereas for “CIP” alternative, concrete trucks and pavers are used, the following assumptions are made:

1. The environmental impacts related to materials are identical for the two alternatives.
2. Trucks are used for both alternatives to transport the same quantity of materials, and, therefore, the environmental impacts related to the use of trucks are identical.

As a result, the differences in the environmental impacts between the two rigid pavement alternatives stem from (1) the use of truck-mounted crane in “PCP” versus the use of concrete paver in “CIP”, and (2) the transportation of concrete paver in “CIP” only. In order to quantify these two components, an additional in-depth modeling is performed for the paving process of the concrete full depth repair activity to isolate equipment environmental impacts from the overall environmental impacts during on-site and transportation processes as follows:

1. The environmental impacts of the concrete paving process are calculated based on the difference between a typical full depth repair activity and a full depth removal activity.
2. The environmental impacts due to equipment use are calculated by comparing the values of maintenance phase assuming the entire pavement is rehabilitated against manufacturing phase with only material-related environmental impacts. The proportions of material-related and equipment-related environmental impacts are obtained.

3. The combination of results from Step 1 and 2 provides the environmental impacts of concrete paver operations. Using the emission factors by Tetra Tech (2015) and USEPA (2015) shown in Table 20, the environmental impacts of equipment use for a crane can be calculated. For Human Health criterion measured by $PM_{2.5}$, the emission factor of PM_{10} is used for equipment due to data limitations. For criteria in which no emission factors are provided, the environmental impacts are assumed to be equal. The operating time for the two types of equipment is also taken into consideration, in which the crane is being used for a shorter duration than the concrete paver.
4. The equipment transportation environmental impacts are assumed to be independent from the quantities of materials being transported. Then incremental values of material quantities are used to obtain various results of overall transportation environmental impacts. Regression analysis is performed to find the portion of the overall transportation environmental impacts that is constant, which corresponds to equipment transportation environmental impacts.
5. The environmental impacts for equipment operations from Step 3 and the results from Step 4 combined reflects the overall difference in environmental impacts for the full depth repair activity using PCP compared to CIP. The overall environmental impacts for PCP can be calculated accordingly based on the results from the "CIP" alternative.

Table 20 Emission Factors for Concrete Paver and Crane

Equipment	Engine Size	NO_x	PM_{10} a/	SO_2	CO_2	CH_4	N_2O	gal/hp-hr b/
Paver	175 < HP <= 300	2.23	0.13	0.004	536	0.031	0.014	0.053
Crane	175 < HP <= 300	1.67	0.08	0.004	531	0.03	0.013	0.052
Global warming potential factor: CO_2= 1, CH_4=25, N_2O =298								

Source: Tetra Tech (2015), USEPA (2015)

With all inputs and methodology defined, the agency LCA results are generated in Athena Pavement LCA in various forms, including total and non-renewable primary energy use, fossil fuel consumption, and global warming potential. Table 21 shows the summary of LCA results for the maintenance phase in a comparative manner, where the “Traditional” alternative is considered as the benchmark for flexible pavement alternatives and the “CIP” alternative is considered as the benchmark for rigid pavement alternatives.

Table 21 Comparative Summary of LCA Results by Athena Pavement LCA

Criteria		GWP	TPE	NRE	FFC	AP	ODP	HHC	EP	SP
Flexible Pavement	Traditional	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recycling	70.4%	65.7%	65.7%	65.7%	71.9%	72.6%	66.8%	72.6%	74.3%
	WMA	97.3%	98.9%	98.9%	98.9%	98.6%	97.6%	99.2%	99.4%	99.5%
	CIR	41.5%	52.8%	52.8%	52.8%	38.6%	37.1%	48.8%	37.5%	33.6%
	FDR	38.5%	47.9%	47.9%	47.9%	36.1%	34.8%	44.5%	35.2%	32.0%
	IC	87.3%	87.3%	87.3%	87.3%	87.3%	87.3%	87.3%	87.3%	87.3%
Rigid Pavement	CIP	100%	100%	100%	100%	100%	100%	100%	100%	100%
	PCP	85.9%	86.0%	86.1%	86.4%	87.3%	99.9%	86.0%	87.1%	90.2%

Notes:
GWP: Global Warming Potential
PEC: Total Primary Energy
NRE: Non-renewable Energy
FFC: Fossil Fuel Consumption
AP: Acidification Potential
ODP: Ozone Depletion Potential
HHC: Human Health Criteria
EP: Eutrophication Potential
SP: Smog Potential

As discussed in the previous section, the overall life cycle environmental impacts during the maintenance phase include impacts from materials, equipment operations, and transportation, while the initial construction and road use phases are excluded from the research scope. The LCA results in absolute values measured by total primary energy, non-renewable energy, fossil fuel consumption, acidification potential, global warming potential, HH criteria, ozone depletion potential, smog potential, and eutrophication potential are listed in Appendix III.

Based on the results of comparative LCA, the following observations are made:

- Within each alternative, the total primary energy, non-renewable primary energy, and fossil fuel consumption results are highly similar, indicating that there is minimum use of renewable energy during the MRR practices of roadways.

- For flexible pavement alternatives, those involving asphalt recycling techniques, including recycling through HIPR, CIR, and FDR, provide major reductions of life cycle environmental impacts under all parameters because of decreased quantities of virgin materials needed. CIR and FDR have achieved even more life cycle environmental impact reductions than recycling through HIPR.
- The “WMA” alternative delivers limited life cycle environmental impact reductions in all parameters compared to the “Traditional” alternative. The “IC” alternative generates greater life cycle environmental impact reductions compared to “WMA” alternative.
- For rigid pavement alternatives, “PCP” alternative creates lower life cycle environmental impacts in all criteria when compared to the “CIP” alternative.

5.2.2 User Life Cycle Assessment

To quantify the life cycle environmental impacts of road users due to the execution of MRR activities, the following inputs for MOVES are assumed or obtained from software defaults, government reports and databases, and other existing literature:

- Traffic volume by annual average daily traffic (AADT) (NYSDOT 2015);
- Hourly traffic distribution (software defaults);
- Traffic composition measured by percentage of trucks (NYSDOT 2015);
- Vehicle age distribution (NYSDOT 1997);
- Link distance (Assumed);
- Link speeds (Carlson and Austin, 1997); and
- Operation mode distribution (Qi et al. 2016).

To maintain consistency with the agency LCA, the work zone that road users drive through is also one mile in length. However, due to the fact that the work zone speed limits are usually lower than the regular speed limits, the existence of work zone will create a shockwave to the upstream section of the road, where vehicles are expected to slow down and merge to the open lane. Similarly, once vehicles drive past the work zone, they will most likely accelerate and resume to regular speed shortly. Therefore, vehicle speeds in upstream, work zone, and downstream segments are different from the regular speeds without a work zone.

A two-lane three-link demonstration roadway section is developed to estimate user environmental impacts using MOVES based on a section of I-481 interstate highway at Onondaga Town Line / Syracuse City Line. Figure 12 shows a sketch of the roadway with upstream link of 0.5 mile, work zone link of 1 mile, and downstream link of 0.5 miles Traffic information and vehicle age distribution are listed in Table 22 with slight simplification from the original NYSDOT data.

Table 22 Traffic Information and Vehicle age distribution inputs for MOVES

Data Type	Values								Sources
Traffic Information	AADT = 30,000; 13% Truck								NYSDOT 2015
Vehicle Age Distribution for Cars: Age and Percentage	**0**	**1**	**2**	**3**	**4**	**5**	**6**		NYSDOT 1997
	0.05	0.07	0.08	0.07	0.06	0.06	0.06		
	7	**8**	**9**	**10**	**11**	**12**	**13**		
	0.07	0.08	0.08	0.08	0.07	0.05	0.04		
	14	**15**	**16**	**17**	**18**	**19**	**20**		
	0.02	0.01	0.01	0.01	0.01	0.01	0.01		
Vehicle Age Distribution for Trucks: Age and Percentage	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
	0.01	0.02	0.02	0.02	0.06	0.07	0.07	0.06	
	8	**9**	**10**	**11**	**12**	**13**	**14**	**15**	
	0.06	0.06	0.07	0.08	0.08	0.08	0.06	0.03	
	16	**17**	**18**	**19**	**20**	**21**	**22**	**23**	
	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.01	

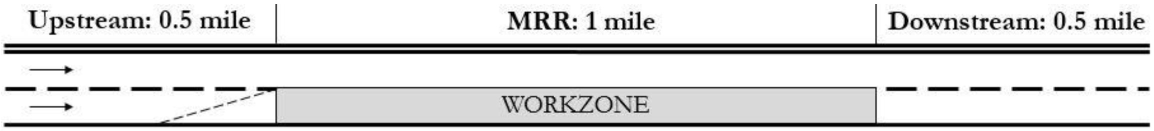


Figure 12 Sketch of Roadway Section with Three Links used in MOVES

Regarding the vehicle operation mode distribution used for each link, Qi et al. (2016) concludes that the percentage of vehicles at different operation modes may be determined by the average speed range, as shown in Table 23. The suggested values indicate that as the vehicle average speed decreases, an increased portion of vehicles will perform braking, low speed coasting, and low speed cruise or acceleration.

Table 23 Vehicle Operation Mode Distribution and Speed by Qi et al. (2016)

Operation Distribution vs Speed (mph)	**60–70**	**50–60**	**40–50**	**30–40**	**10–20**
Braking	0.024	0.05	0.078	0.105	0.138
Idling	0	0	0	0	0.012
Low Speed Coasting; VSP< 0; 1<=Speed<25	0	0	0.003	0.016	0.288
Cruise/Acceleration; 0<=VSP< 3; 1<= Speed<25	0	0	0.004	0.013	0.332
Cruise/Acceleration; 3<=VSP< 6; 1<=Speed<25	0	0	0	0.008	0.11
Cruise/Acceleration; 6<=VSP< 9; 1<=Speed<25	0	0	0	0.003	0.041
Cruise/Acceleration; 9<=VSP<12; 1<=Speed<25	0	0	0	0.002	0.013
Cruise/Acceleration; 12<=VSP; 1<=Speed<25	0	0	0	0	0.03
Moderate Speed Coasting; VSP< 0; 25<=Speed<50	0	0.01	0.167	0.222	0.019
Cruise/Acceleration; 0<=VSP< 3; 25<=Speed<50	0	0.006	0.111	0.151	0.004
Cruise/Acceleration; 3<=VSP< 6; 25<=Speed<50	0	0.008	0.148	0.153	0.001
Cruise/Acceleration; 6<=VSP< 9; 25<=Speed<50	0	0.008	0.106	0.138	0.002
Cruise/Acceleration; 9<=VSP<12; 25<=Speed<50	0	0.004	0.078	0.074	0.001
Cruise/Acceleration; 12<=VSP<18; 25<=Speed<50	0	0.003	0.095	0.058	0.001
Cruise/Acceleration; 18<=VSP<24; 25<=Speed<50	0	0.001	0.025	0.012	0
Cruise/Acceleration; 24<=VSP<30; 25<=Speed<50	0	0	0.007	0.004	0
Cruise/Acceleration; 30<=VSP; 25<=Speed<50	0	0.001	0.014	0.021	0.009
Cruise/Acceleration; VSP< 6; 50<=Speed	0.238	0.33	0.058	0.008	0
Cruise/Acceleration; 6<=VSP<12; 50<=Speed	0.337	0.315	0.046	0.003	0
Cruise/Acceleration; 12<=VSP<18; 50<=Speed	0.242	0.162	0.023	0.003	0
Cruise/Acceleration; 18<=VSP<24; 50<=Speed	0.098	0.051	0.016	0	0
Cruise/Acceleration; 24<=VSP<30; 50<=Speed	0.024	0.013	0.003	0	0
Cruise/Acceleration; 30<=VSP; 50<=Speed	0.035	0.038	0.016	0.006	0

To determine the additional user environmental impacts of lane closure scenario compared to regular scenario where there is no work zone, a more detailed analysis is conducted following the diagram shown in Figure 13.

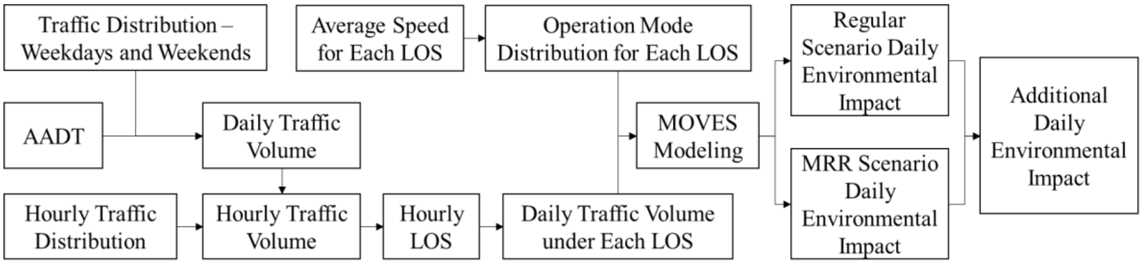


Figure 13 Diagram for User Environmental Impact using MOVES

Due to the fact that traffic volume varies within a single day and between weekdays and weekends, it is necessary to calculate the hourly level of service (LOS) for both weekdays and weekends to reflect the degree of congestion and determine the average speed under each LOS. The default values in MOVES for hourly distribution of daily traffic and daily distribution of traffic within a week in Onondaga County are used to obtain hourly traffic volume under an AADT of 30,000, as shown in Figure 14. Then, hourly LOS can be calculated based on average vehicle spacing (see Table 24) following the definitions by 2010 Highway Capacity Manual.

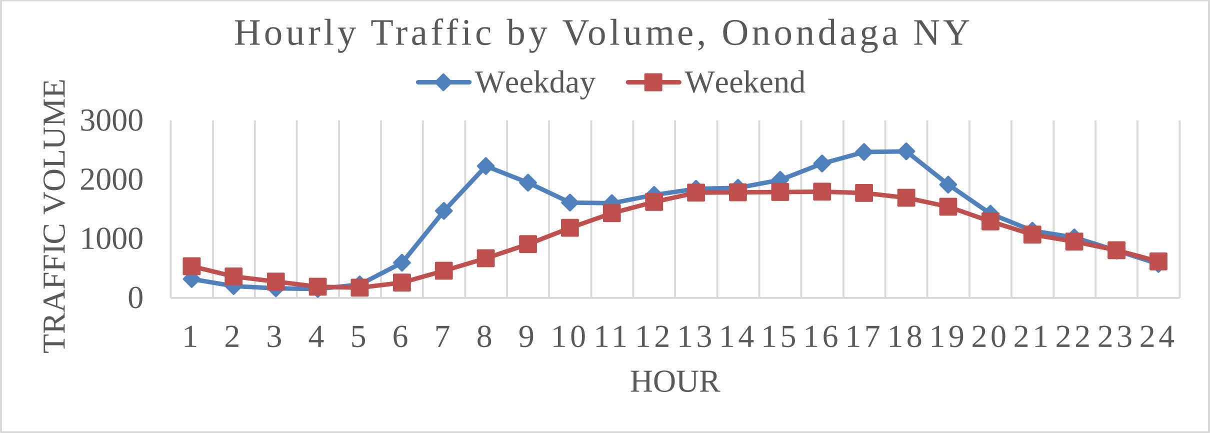


Figure 14 Hourly traffic distribution for demonstration highway section

Table 24 Vehicle Spacing under each level of service.

Level of Service (LOS)	Description	Lowest average Vehicle Spacing (ft)
A	Free flow	550
B	Reasonably free flow	330
C	Stable flow	220
D	Approaching unstable flow	160
E	Unstable flow, operating at capacity	120
F	Forced or breakdown flow	<120

Two lanes are used to serve the hourly traffic volumes when calculating average vehicle spacing to determine hourly LOS for regular traffic scenario. In the case of one lane closure due to MRR activities, assuming daily and hourly traffic volumes remains the same with the regular traffic scenario, the vehicle density in the upstream link, where merging actions take place, is expected to increase dramatically, resulting in a lower LOS compared to the regular traffic scenario (e.g. from LOS of B in regular scenario to LOS of E in lane closure scenario). After merging is completed and vehicles enter the work zone, they are expected to maintain a speed of 45 mph until they reach the downstream link, where they would most likely accelerate to the regular speeds shortly.

For both scenarios, regular and MRR, the daily traffic volumes under each LOS are calculated as shown in Table 25.

Table 25 Daily traffic volumes under each level of service for regular scenario and MRR scenario

		Daily Traffic volumes under each LOS					
Level of Service (LOS)		A	B	C	D	E	F
Regular	Weekday	5170	17402	9447	0	0	0
	Weekend	7374	17577	0	0	0	0
MRR	Weekday	1052	1166	1818	4028	12516	11441
	Weekend	1250	2278	3730	3910	13784	0

The average vehicle speeds under each LOS adopted by EPA are shown in Table 26. The inputs used for MOVES are rounded to integers with LOS A through C of 60 mph, LOS D of 53 mph, LOS E of 30 mph, and LOS F of 19 mph. EPA also specified a "high speed" of approximately 63 mph on top of LOS A through C, and this speed is selected for the average speed under regular traffic scenario where there are no flow restrictions. A summary of average speed values for each scenario and link is shown in Table 27. With these speed values, the operation mode distribution can be determined by referring to the suggested values in corresponding columns in Table 23. Appendix IV shows the detailed vehicle operation mode distribution for each link under both regular traffic and MRR scenarios.

Table 26 Average Speed in mph under each level of service

Level of Service (LOS)	A – C	D	E	F
Average Speed	59.7	52.9	30.5	18.6

Source: Carlson and Austin. (1997)

Table 27 Average Speed in mph for scenarios and links

Link	Distance	Regular Scenario	MRR Scenario			
			LOS A-C	LOS D	LOS E	LOS F
Upstream	0.5 mile	63	60	53	30	19
MRR	1 mile	63	45	45	45	45
Downstream	0.5 mile	63	60	60	60	60

As all inputs required for MOVES become available, modeling is performed for five different speed combinations shown in Table 27 with one for regular scenario and four for MRR scenarios. The modeling results show a number of environmental impacts such as CO_2 equivalent emissions, fossil energy use, and total energy use. After comparing the modeling results of MRR scenarios with their counterparts of Regular scenario, the daily additional environmental impacts due to lane closure caused by MRR activities are obtained considering the daily traffic volume under each LOS shown in Table 25.

These environmental impacts calculated with MOVES are generated due to fuel combustions in engines of cars and trucks, while the "upstream" environmental impacts generated during the production and transportation of fuels can be obtained from the GREET® model where the "Well-to-Pump" environmental impacts of a variety of products including E10 gasoline and conventional diesel are provided. Table 28 shows the GREET® data relevant to this research. With the production and transportation environmental impacts combined with combustion environmental impacts, the daily additional user life cycle environmental impacts are calculated as shown in Table 29.

Table 28 "Well to Pump" Environmental Impact Per 1 MJ of Product from GREET

	Greenhouse Gas (g)	Fossil Energy (KJ)	Total Energy(KJ)
E10 Gasoline	24.27	1200	1286
Conventional Diesel	18.38	1204	1210

Table 29 Daily additional life cycle environmental impacts

	CO_2_Equiv(kg)	Fossil Energy (MJ)	Total Energy(MJ)
Weekday	3806	83892	90907
Weekend	2047	45081	48925

In order to identify the overall environmental impacts during MRR activities throughout the analysis period, the duration of lane closure on weekdays and weekends are needed for each alternative over 60 years. RSMeans is the primary source used to estimate time needed for each activity based on typical daily production rate. Other miscellaneous sources regarding curing time needed for certain techniques such as CIR, FDR, and concrete paving have also been investigated. The duration of lane closure needed for each project alternative throughout the life cycle is listed in Table 30 measured by number of weekdays and weekends per lane. Combining the daily additional environmental impacts (Table 29) with duration of lane closure in days

(Table 30), the overall life cycle environmental impacts per lane can be calculated as shown in Table 31.

Table 30 Lane closure durations per lane for each alternative over life cycle

Alternative	Lane Closure Days	
	Weekday	Weekend
Traditional	172	50
Recycling	103	20
WMA	172	50
CIR	103	20
FDR	106	26
IC	166	50
CIP	114	38
PCP	83	26

Table 31 User environmental Impacts for each alternative per lane

Alternative		CO_2_Equiv(kg)	Fossil Energy (MJ)	Total Energy(MJ)
Flexible Pavement	Traditional	7.57E+05	1.67E+07	1.81E+07
	Recycling	4.33E+05	9.54E+06	1.03E+07
	WMA	7.57E+05	1.67E+07	1.81E+07
	CIR	4.33E+05	9.54E+06	1.03E+07
	FDR	4.57E+05	1.01E+07	1.09E+07
	IC	7.34E+05	1.62E+07	1.75E+07
Rigid Pavement	CIP	5.12E+05	1.13E+07	1.22E+07
	PCP	3.69E+05	8.14E+06	8.82E+06

Assuming that MRR activities taking place in the closed lane are independent from the vehicle operations on the open lane, the user life cycle environmental impacts are solely related to the duration of lane closure. Therefore, alternatives that require longer periods of lane closures (e.g. “Traditional” and “WMA”) have higher life cycle user environmental impacts compared to the ones that require shorter periods of lane closure (e.g. “CIR and FDR”). For rigid pavement alternatives, “PCP” results in lower user life cycle environmental impacts compared to “CIP”, which is a major motivation to implement precast concrete pavement systems despite potentially higher agency costs.

5.2.3 Summary of Life Cycle Assessment Results

The combined results of agency LCA and user LCA are shown for each alternative per lane with respect to global warming potential measured by CO_2 equivalent emissions (Figure 15), fossil fuel consumption (Figure 16), and total energy consumption (Figure 17). Detailed results are listed in Appendix V.

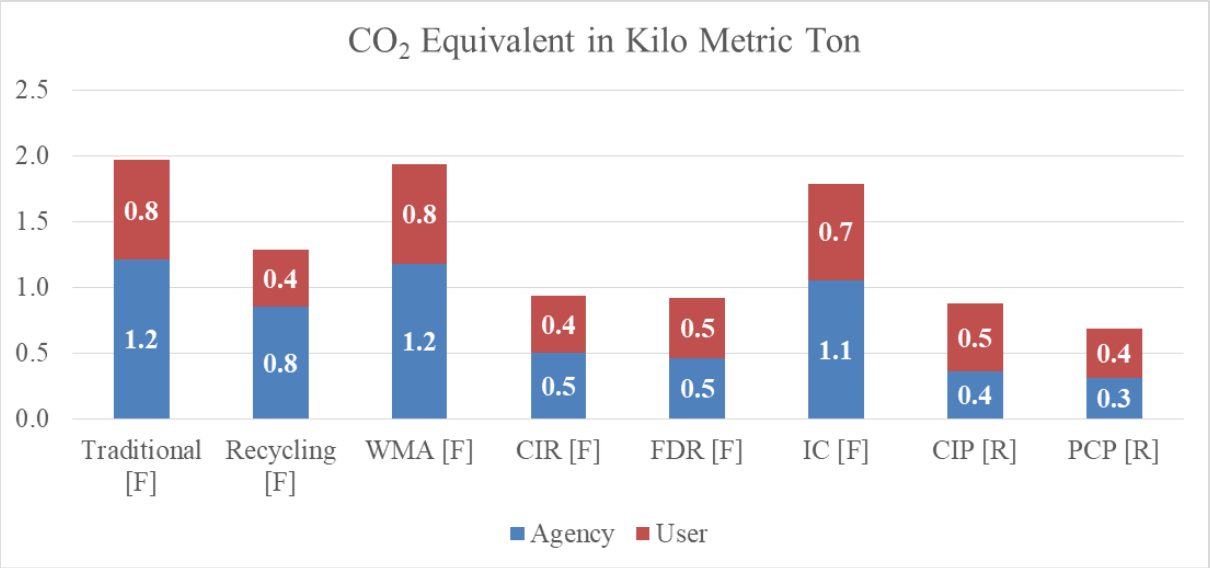


Figure 15 Life Cycle CO2 equivalent emissions

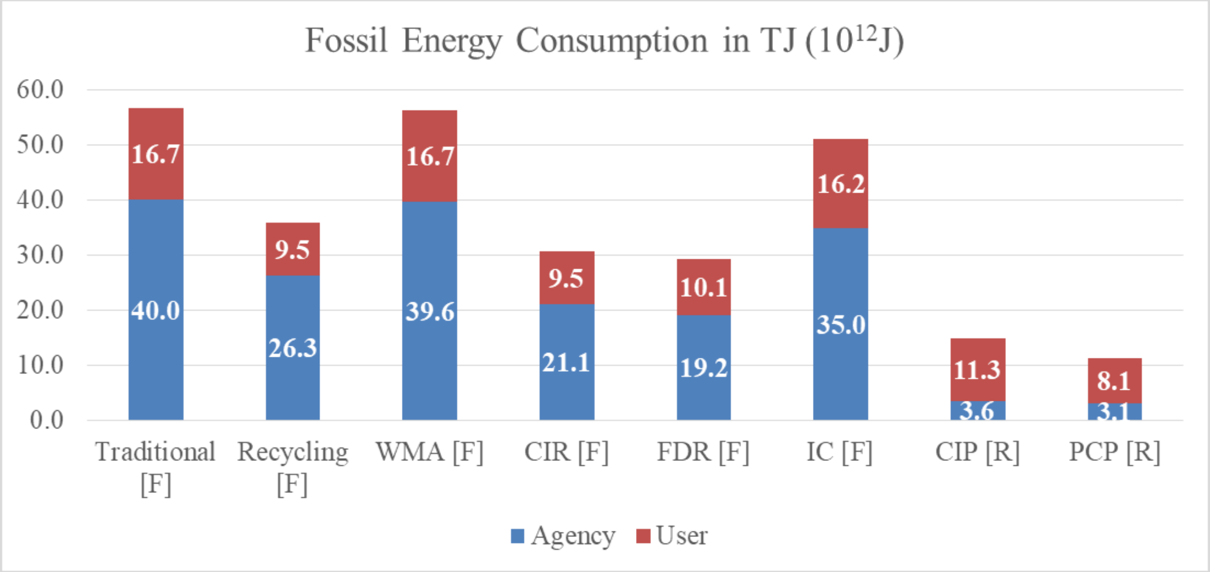


Figure 16 Life Cycle Fossil Energy Consumption

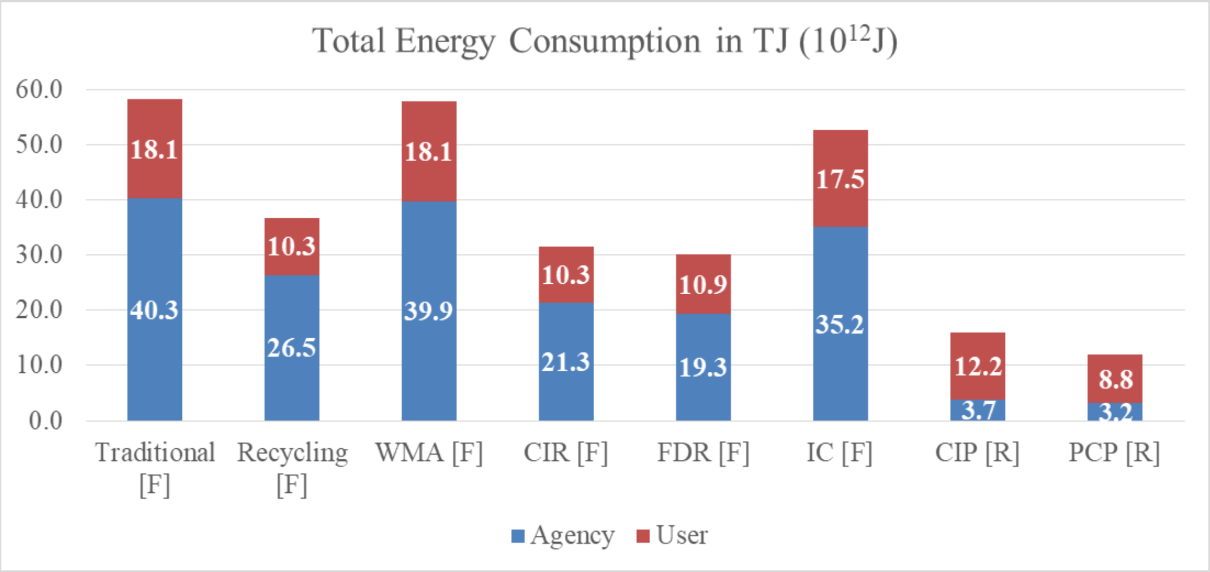


Figure 17 Life Cycle Total Energy Consumption

Results show that regarding these three major life cycle environmental impact categories, agency impacts account for a large portion of the overall environmental impacts, which verifies the importance of taking agency life cycle environmental impacts into consideration during decision-making processes.

Flexible pavement MRR alternatives that involve recycling, including “Recycling”, “CIR”, and “FDR” create lower overall life cycle environmental impacts than other flexible pavement alternatives. Similarly, “PCP” alternative for rigid pavement creates lower overall environmental impacts compared to “CIP” alternative over the life cycle.

Public agencies can utilize these results in the determination of MRR project alternatives according to their specific goals and objectives in terms of sustainability. These results can also provide estimates on the potential reductions of life cycle environmental impacts by switching to non-traditional or accelerated alternatives from traditional techniques.

5.3 Life Cycle Cost Analysis of Economic and Social Impacts

Out of the same consideration with LCA of project alternatives, the life cycle cost analysis (LCCA) of this research focuses only on the costs incurred during the execution of MRR activities and excludes cost entries such as the roadway initial construction costs and user costs before and after the MRR activities. Specifically, the components of LCCA are (1) agency costs on MRR activities, (2) user costs due to additional fuel consumption, (3) user costs due to travel time delay, and (4) user costs due to increased number of crashes. These components cover the majority of direct social-economic impacts of MRR activities.

The primary data sources of LCCA for agency costs are survey results by Salman et al. (2017), state DOT and FHWA reports, and RSMeans; while data sources of LCCA for user costs include U.S. Department of Energy (USDOE), U.S. Department of Transportation (USDOT), DataUSA, New York State Department of Transportation (NYSDOT), National Highway Traffic Safety Administration (NHTSA), as well as RSMeans.

5.3.1 Agency Life Cycle Cost Analysis

Through the national survey of state DOTs, data regarding the costs of implementing WMA overlay, CIR, and FDR were collected with sample sizes of 10, 10, and 8, respectively. Cost data regarding IC is obtained from literature, where on average the IC instrumentations incur an additional cost of 3% (Bledsoe 2015). The costs of performing Crack Seal, Patch, Mill and HMA Fill, and Recycling using HIPR are calculated using RSMeans 2016, which also provides supplementary information to cost entries in WMA overlay, CIR, and FDR alternatives with adjustments of localities. Table 32 summarizes the national average cost of all the activities.

Table 32 Cost Information of MRR Activities

MRR Activities	Quantities and Specifications	Cost in K$/ lane
Crack Seal	3/8" wide 1" depth, 1000ft / ln	2.2
	3/8" wide 1" depth, 1500ft / ln	3.3
	3/8" wide 1" depth, 3750ft / ln	8.3
	3/8" wide 1" depth, 4500ft / ln	10.0
Patch	2% Lane area, 3 inch deep	13.8
	3% Lane area, 3 inch deep	21.1
Mill and HMA Fill	4"(2" binder + 2" wearing)	358.5
	2" wearing course, no shoulder	136.6
Hot In-Place Recycling	Recycle 4" + 2" HMA wearing course	268.8
Warm Mix Asphalt	4" Overlay	341.0
	2" Overlay, no shoulder	130.4
Cold In-Place Recycling	Recycle 4"+ 2" HMA wearing course	271.2
Full Depth Reclamation	Recycle 6"+ 2" HMA wearing course	369.5
Intelligent Compaction	4" Paving	369.2
	2" Paving, no shoulder	140.7
Concrete Joint Seal	1/2" wide 2" depth, 4400 ft/ln-mile	7.8
	1/2" wide 2" depth, 6600 ft/ln-mile	11.7
Concrete Partial Depth Repair	2% lane area, 2 inch deep	19.5
	5% lane area, 2 inch deep	48.8
Concrete Full Depth Repair	10% lane area	133.9
	15% lane area	200.8
Concrete Full Depth Repair using Precast Concrete Slabs	10% lane area	295.2
	15% lane area	442.8
Diamond Grinding	Grind 0.2 inch off 100% lane area	49

The cost entries over the analysis period of 60 years can be obtained. Table 33 shows the example of “Traditional” alternative, and cost entries of all alternatives are listed in Appendix II under “Cost/lane (K$)” column. With a discount rate of 4%, a cost breakdown over the analysis period is developed in Figure 18 for the same alternative, where all future cost entries are discounted to present values in 2016 U.S. dollars. Similarly, the life cycle costs for other alternatives are calculated based on respective cost entries over 60 years, and a sensitivity analysis is conducted with different values of discount rates from 3% to 7%. Table 34 shows the results of agency LCCA in present values measured in 1,000 USD per lane.

Table 33 Cost Entries of "Traditional" Alternative

Year	MRR Activity	Detail	Cost in K$/ln
0	M&F HMA	4" (2" wearing + 2" binder)	358.5
3	Crack Seal	1000 ft/ln	2.2
6	Crack Seal	3750 ft/ln	8.3
10	Patch	2% Lane area	13.8
15	M&F HMA	2" wearing course, no shoulder	136.6
21	Patch	3% Lane area	21.1
24	M&F HMA	4" (2" wearing + 2" binder)	358.5
27	Crack Seal	1500 ft/ln	3.3
30	Crack Seal	4500 ft/ln	10.0
34	Patch	2% Lane area	13.8
39	M&F HMA	2" wearing course, no shoulder	136.6
45	Patch	3% Lane area	21.1
48	M&F HMA	4" (2" wearing + 2" binder)	358.5
51	Crack Seal	1500 ft/ln	3.3
54	Crack Seal	4500 ft/ln	10
58	Patch	2% Lane area	13.8

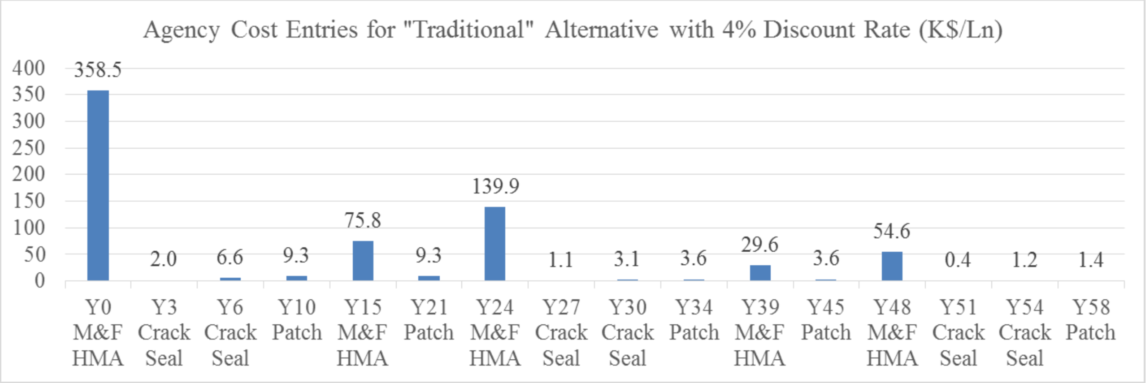


Figure 18 Agency Cost Entries of "Traditional" Alternative with 4% Discount Rate

Table 34 Life Cycle Costs of Alternatives with Different Discount Rates

Alternative		Agency Life Cycle Costs in K$				
		DR=3%	DR =4%	DR=5%	DR=6%	DR=7%
Flexible Pavement	Traditional	1609	1400	1249	1137	1053
	Recycling	1298	1123	996	902	832
	WMA	1536	1336	1191	1085	1005
	CIR	1306	1131	1003	909	838
	FDR	1540	1335	1190	1086	1010
	IC	1556	1349	1204	1099	1022
Rigid Pavement	CIP	2005	1785	1636	1534	1461
	PCP	3444	3079	2834	2666	2549

Major observations on agency LCCA results include:

- For flexible pavement alternatives, “CIR” and “Recycling” alternatives have the lowest life cycle costs.
- The life cycle costs of “Traditional” and “WMA” alternatives are highly comparable; the life cycle costs of “FDR” and “IC” alternatives are slightly lower than the “Traditional” alternative.
- For rigid pavement alternatives, life cycle costs of “PCP” are much higher than “CIP”.
- The absolute values of agency LCCA results are highly sensitive to the discount rates.

In addition, part of the cost data for WMA overlay, CIR, and FDR activities are obtained from survey by Salman et al. (2017) with relatively small sample sizes, which may not provide results as representative as those estimated using RSMeans. Therefore, the relatively low agency costs for “WMA”, “CIR”, and “FDR” alternatives may not be readily achievable, especially if contractor availability is limited.

5.3.2 User Life Cycle Cost Analysis

In evaluating user-related economic and social impacts, costs of travel time delay, costs of additional fuel consumption, and costs of increased crash events are considered in the user LCCA. Daily costs of travel time delay are calculated based on the additional travel time of each vehicle due to MRR activities, the value of time for each vehicle, and daily traffic volume on weekdays and weekends. Daily costs of additional user fuel consumption are calculated based on the daily additional fossil fuel consumption using MOVES results, energy density of fuels, and unit costs of fuels. Daily costs of increased crash events are calculated based on daily additional number of crashes along with costs of crashes.

5.3.2.1 Costs of Travel Time Delay

Using the average speeds of links from Table 27, the total additional travel time per vehicle under each LOS can be obtained as shown in Table 35. Combining this information with the daily traffic volumes under each LOS (shown in Table 30), the daily additional travel time can be calculated as 543 vehicle-hours on weekdays and 297 vehicle-hours on weekends.

Table 35 Additional Travel Time per Vehicle under each LOS

Link	Distance	Regular Scenario	MRR Scenario			
			LOS A-C	LOS D	LOS E	LOS F
Upstream	0.5 mile	63	60	53	30	19
MRR	1 mile	63	45	45	45	45
Downstream	0.5 mile	63	60	60	60	60
Travel Time (Second)						
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
Additional Travel Time (Second)			**25.71**	**29.68**	**55.71**	**90.45**

To determine the appropriate monetary value of user travel time under the specific conditions in this research, the following observations are used:

- According to the guidelines by USDOT (2011) regarding the value of travel time, for passenger cars, local personal travel, intercity travel, and business travel are valued at 50%, 70%, and 100% of hourly income, respectively.
- The Passenger Travel Factors and Figures by USDOT (2015) also concluded that in 2009, 25% of personal total miles traveled are for work and work-related purposes.
- Daily traffic distribution of Onondaga County from MOVES database shows that peak-hour traffic volume accounts for more than half of daily traffic volume.

Therefore, the following assumptions are made:

- All truck travels are assumed to be work-related.
- Intercity traffic volumes are assumed to remain constant throughout the day.
- Peak hour traffic consists of both local traffic and intercity traffic, while non-peak hour traffic consists of only intercity traffic.

As a result, it is calculated that for passenger cars, 70% of personal travels are local travels while the remaining 30% are intercity travels. Then the overall fractions of passenger car traffic include 25% for work-related traffic, 52.5% for local personal traffic, and 22.5% for intercity personal traffic. Based on the USDOT guidelines, the overall value of time for passenger cars is 67% of hourly income. According to DATAUSA, the 2016 median household income for Onondaga County, NY, is $57,365, and the average vehicle occupancy by NYSDOT (2012) is 1.67 for passenger cars and 1.057 for trucks. Therefore, considering truck traffic accounts for 13% of the overall traffic, the value of time is calculated as $30.64 per vehicle-hour, and the daily additional costs of travel time delay are $16,641 for weekdays and $9,111 for weekends.

The user life cycle cost of travel time delay can be obtained as shown in Figure 19 for "Traditional" alternative as an example. Detailed results are included in Appendix VI.

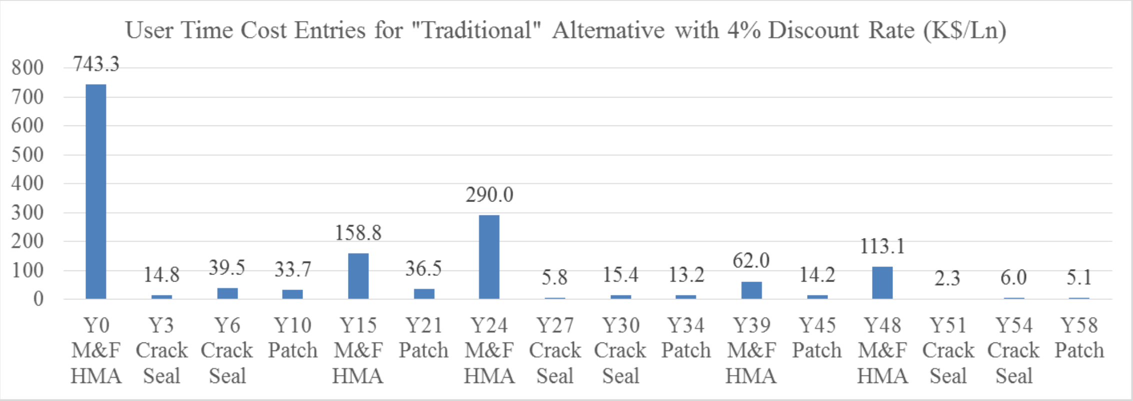


Figure 19 User Time Cost Entries of "Traditional" Alternative with 4% Discount Rate

5.3.2.3 Costs of Additional Fuel Consumption

Based on the user environmental impacts from MOVES, the additional fossil fuel consumption in MJ can be calculated for passenger cars and trucks under each LOS, as shown in Table 36. The energy density values for gasoline and diesel fuels are obtained from EPA as 137.16 MJ/Gallon and 144.54 MJ/Gallon, respectively. The fuel costs in Onondaga County as of August 2016, as reported by USDOE, are \$2.219/Gallon and \$2.406/Gallon for gasoline and diesel, respectively. 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.

Table 36 Additional Fossil Fuel Consumption in MJ per Vehicle under each LOS

LOS	Passenger Car	Truck
ABC	0.180	0.240
D	0.218	0.292
E	0.438	0.562
F	0.898	0.758

Based on the rehabilitation schedule for each alternative and the durations of lane closure, the additional life cycle user fuel costs can be calculated. Figure 20 shows an example of “Traditional” alternative using a discount rate of 4%. The full results are listed in Appendix VI.

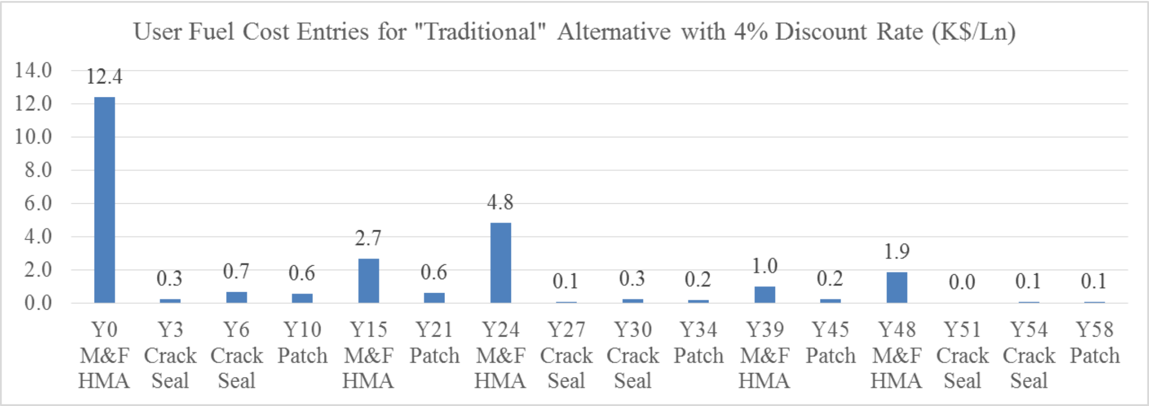


Figure 20 User Fuel Cost Entries of “Traditional” Alternative with 4% Discount Rate

5.3.2.4 Costs of Increased Crash Events

Due to the existence of work zone where MRR activities are being performed, assuming daily traffic volumes remain constant, the v/c ratio is going to increase, which results in changes in the crash rate based on previous studies. Under the same configurations used in MOVES, the change in crash rates that leads to potentially increased crash events occur most significantly at the upstream link, where vehicle merging occurs before entering the single-lane work zone. Therefore, the impacts of increased v/c ratios on crash rates are investigated only for the upstream link, since traffic conditions in MRR and downstream links are not as complex.

The capacity per lane of the interstate highway in this research is calculated using the relevant equations from Highway Capacity Manual 2000:

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID} \tag{2}$$

Where:

FFS = Free Flow speed
$BFFS$ = base free flow speed
f_{LW} = adjustment factor for lane width
f_{LC} = adjustment factor for right shoulder lateral clearance
f_N = adjustment factor for number of lanes
f_{ID} = adjustment factor for interchange density

BFFS is set at 70 mph for urban highways; f_{LW} is selected as 0.0 based on the lane width of 12 feet; f_{LC} is selected as 0.0 for two lanes in one direction with right shoulder width of 6 feet; f_N is selected as 4.5 for 2 lanes; and f_{ID} is selected as 1.0 for small urban area size. Therefore, FFS is calculated as 64.5 mph.

$$BaseCap = 1{,}700 + 10FFS;\ for\ FFS <= 70 \tag{3}$$

$$PeakCap = BaseCap * PHF * N * f_{HV} * f_p \tag{4}$$

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} \tag{5}$$

Where:

PHF = Peak Hour Factor
N = Number of lanes in one direction
f_{HV} = Adjustment factor for heavy vehicles
f_p = Adjustment factor for driver population
P_T = Proportion of trucks and buses in the traffic stream, expressed as a decimal
E_T = Passenger-car equivalents = 1.5 for all urban freeways

Peak hour factor is 0.90 for initial v/c below 0.81 and 0.95 for initial v/c above 0.9025. For initial v/c values in between 0.81 and 0.9025, PHF = $(0.9025*v/c)^{0.5}$ / 0.95; N equals to 1 for MRR scenario; P_T is 0.13; f_p is 1.0 for urban freeways. The peak capacity is then obtained as between 1982 and 2092 depending on the PHF values used. With hourly traffic volume available from MOVES, hourly v/c ratios can be calculated.

Research by Zhou and Sisiopiku (1997) established relationship between v/c ratios and crash rates for weekdays and weekends, where crash rates measured by number of accidents per 100 million vehicle miles traveled (100 MVMT) are related to v/c ratios in the following polynomial equations:

$$\text{Weekdays: Accident} = 488\,(v/c)^2 - 494\,(v/c) + 248 \tag{6}$$

$$\text{Weekends: Accident} = 592\,(v/c)^2 - 755\,(v/c) + 312 \tag{7}$$

Based on the hourly v/c ratios under MRR and regular traffic scenarios, the changes in hourly crash rates are calculated. Therefore, the number of daily additional crashes per 100 MVMT are calculated for weekdays and weekends and shown in Table 37 after integrating the daily traffic volumes respectively. The detailed results are shown in Appendix VII.

Table 37Additional Crashes per 100 MVMT for Weekdays and Weekends

	Weekdays	Weekends
Number of Crashes for 100 MVMT	2748073	-731364

It is noteworthy that on weekends, the number of additional crashes is negative, indicating an improvement in traffic safety caused by MRR activities. This is because the equations by Zhou and Sisiopiku (1997) have optimum values of v/c ratios (between 0.5 and 0.6 for weekdays and between 0.6 and 0.7 for weekends) to achieve the least numbers of crashes. For very low v/c ratios that most likely represent night and early morning traffic conditions, poor visibility, fatigue, excessive speeding, and higher rates of driving while intoxicated may contribute to higher accident rates. As v/c ratio increases, drivers tend to become more cautious and maintain proper speed, which leads to lower accident rates until very high v/c ratio is reached where major congestion creates higher possibility of multi-vehicle crashes. Because of the work zone in MRR scenario, the weekend hourly v/c ratios are closer to the “safest” value compared to those in regular traffic scenario, leading to a negative number of additional crashes.

The cost of each vehicle crash varies greatly depending on locality, severity, and the boundaries of impacts being considered. According to NYSDOT (2016), direct economic costs of one crash event in 2015 range from $3,800 for a property-damage-only (PDO) scenario to $3,355,700 for a fatal scenario, shown in Table 38.

Table 38 Direct Economic Cost per Crash (NYSDOT 2016)

Crash Classifications	Fatal	Injury	PDO
Direct Economic Cost in 2015 USD	3,355,700	90,100	3,800

NHTSA also concluded that the societal harm from vehicle crashes due to loss of quality-of-life accounts for 71% of the overall impacts, and the remaining 29% corresponds to direct economic costs (Blincoe et al. 2015). These observations form the basis on which the costs of crashes are determined, and an average of $34,583 is calculated as the direct economic cost for each crash event.

Following the same methodology used for calculating cost of user time delay and cost of additional fuel consumption, cost entries can be developed over the life cycle of 60 years for each alternative considering both direct economic cost (29% of the overall cost) and loss of quality-of-life cost (71% of the overall cost). Figure 21 shows an example of "Traditional" alternative using a discount rate of 4%, and detailed results are listed in Appendix VI.

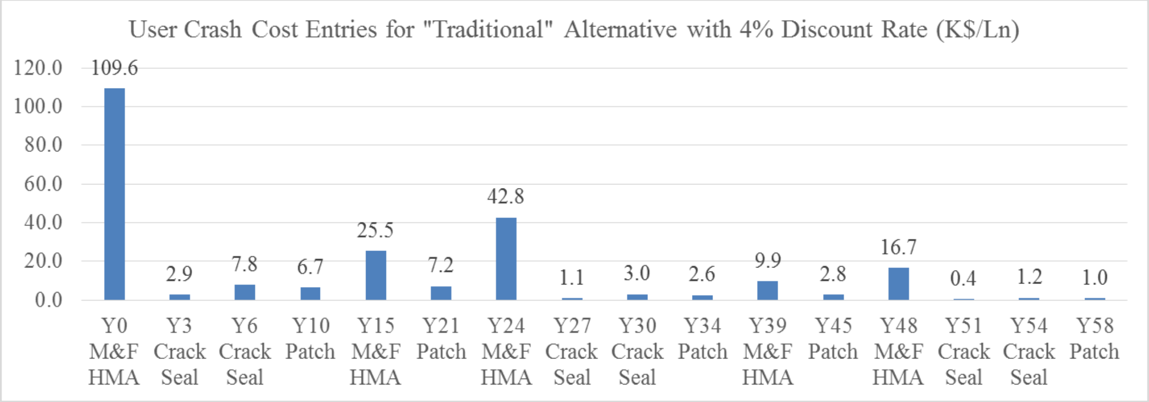


Figure 21 User Crash Cost Entries of "Traditional" Alternative with 4% Discount Rate

5.3.2.4 Summary of User Life Cycle Costs

As discussed before, user life cycle costs consist of (1) costs of travel time delay, (2) costs of additional fuel consumption, and (3) costs of additional crashes.

Using a discount rate of 4%, the total user life cycle costs for each alternative is listed in Table 39, and the sensitivity analysis results using different discount rates from 3% to 7% are summarized in Table 40. Since the calculations of user costs in all three sub-categories are based on lane closure durations, alternatives that require fewer days of lane closure throughout the analysis period have lower user life cycle costs.

Table 39 User Life Cycle Costs using 4% Discount Rate

Alternative		User Life Cycle Costs in K$ (4% discount rate)			
		Time Delay	Fuel	Crash	Total
Flexible Pavement	Traditional	3107	52	483	3642
	Recycling	1646	28	276	1949
	WMA	3107	52	483	3642
	CIR	1646	28	276	1949
	FDR	1682	28	271	1981
	IC	2899	49	449	3396
Rigid Pavement	CIP	2103	35	319	2458
	PCP	1506	25	232	1763

Table 40 Sensitivity Analysis of User Life Cycle Costs

Alternative		User Life Cycle Costs in K$				
		DR=3%	DR =4%	DR=5%	DR=6%	DR=7%
Flexible Pavement	Traditional	4205	3642	3234	2933	2707
	Recycling	2302	1949	1691	1498	1350
	WMA	4205	3642	3234	2933	2707
	CIR	2302	1949	1691	1498	1350
	FDR	2342	1981	1723	1533	1392
	IC	3929	3396	3018	2744	2542
Rigid Pavement	CIP	2797	2458	2224	2058	1939
	PCP	2012	1763	1591	1469	1380

5.3.3 Summary of Life Cycle Cost Analysis Results

With agency LCCA and user LCCA results available, the overall life cycle costs for all alternatives are calculated and summarized in Table 41 using a discount rate of 4%. The sensitivity analysis results of overall life cycle costs are included in Table 42. It is worth noting that the agency life cycle costs are national average values from the survey and RSMeans, whereas user life cycle costs are using data from Onondaga County, NY. Therefore, an adjustment for locality is made by applying a location factor of 0.983 from RSMeans to agency life cycle costs so that the summation of the two cost categories accurately indicates the overall life cycle costs.

Table 41 Life Cycle Costs for Alternatives in Onondaga NY using 4% Discount Rate

Alternative		Life Cycle Costs in K$ (4% discount rate)		
		Agency	User	Total
Flexible Pavement	Traditional	1376	3642	5018
	Recycling	1104	1949	3054
	WMA	1314	3642	4956
	CIR	1111	1949	3061
	FDR	1312	1981	3293
	IC	1326	3396	4722
Rigid Pavement	CIP	877	2458	3335
	PCP	1513	1763	3277

Table 42 Overall Life Cycle Costs for Alternatives in Onondaga NY

Alternative		Overall Life Cycle Costs in K$				
		DR=3%	DR =4%	DR=5%	DR=6%	DR=7%
Flexible Pavement	Traditional	5786	5018	4462	4051	3742
	Recycling	3578	3054	2670	2385	2168
	WMA	5715	4956	4406	3999	3694
	CIR	3586	3061	2677	2391	2174
	FDR	3856	3293	2893	2601	2385
	IC	5459	4722	4201	3825	3547
Rigid Pavement	CIP	3782	3335	3028	2812	2657
	PCP	3705	3277	2984	2779	2633

For flexible pavements, alternatives involving asphalt recycling have lower overall life cycle costs because of both lower agency life cycle costs and lower user life cycle costs. For rigid pavements, “PCP” alternative results in a lower overall life cycle cost in spite of a higher agency life cycle cost compared to “CIP” alternative. However, these results apply to the specific configurations of this research and may change in a different scenario. Public agencies are encouraged to use their own cost information wherever applicable to draw more relevant conclusions.

The fractions of each cost item in the overall life cycle costs are listed in Table 43. Agency costs account for 26% to 40% of overall life cycle costs, with the rest being user costs.

Therefore, it is critical to take into consideration user costs, which account for larger portions. User time delay costs dominate the total user costs, while fuel costs take an extremely small fraction. This is because the demonstration framework uses partial lane closure as the traffic management plan, so the distances that vehicles travel are the same with the regular traffic scenario. The extra fuel costs may be greater if vehicles take detours and travel longer distances than the existing roadway.

Table 43 Fractions of Cost Items in Overall Life Cycle Costs

Alternative		Agency Costs	User Costs		
			Time Delay	Fuel	Safety
Flexible Pavement	Traditional	27%	62%	1%	10%
	Recycling	36%	54%	1%	9%
	WMA	26%	63%	1%	10%
	CIR	36%	54%	1%	9%
	FDR	40%	51%	1%	8%
	IC	28%	61%	1%	10%
Rigid Pavement	CIP	26%	63%	1%	10%
	PCP	46%	46%	1%	7%

5.4 What-if Analysis using the LCA-LCCA Model

In the case of analyzing different strategies using the same MRR technique, such as accelerated construction or other innovative techniques with the potential of reducing the overall impacts, this LCA-LCCA model can be used to perform what-if scenario analysis and support project-level decision-making from a triple bottom line perspective. Two examples are provided for demonstration purposes.

5.4.1 Accelerated Construction

The example of accelerated construction strategy is formulated based on “Traditional” alternative, in which the same set of parameters and specifications are used with the only exception that in Mill & Fill HMA activities (both for 2” and for 4” in depth), the milling crew works overtime for two additional hours per weekday to achieve early completion and are paid twice as much for overtime hours. The expectation of this strategy is to reduce user costs and user emissions by incurring additional agency costs and ultimately achieve lower life cycle costs and environmental impacts.

Relevant RSMeans data needed to perform the what-if scenario analysis of accelerated construction strategy are provided in Table 44. Unit cost for overtime construction is calculated using the following equation:

$$\text{Total unit cost} = M + \frac{L \times Payroll\ factor + E}{Production\ Efficiency} \tag{8}$$

Where M is the material cost, L is the labor cost, and E is the equipment cost. The production efficiency for milling activity of 2” is calculated as 97.5% as it lasts for approximately two weeks, and that for milling activity of 4” is 95% based on the duration of three weeks.

Table 44 Daily Cost and Production Efficiency of Milling

Cost Code	02 41 13.17 5010 and 02 41 13.17 5050				
Activity	Pavement removal, bituminous roads, up to 3” / 4” to 6”				Crew B-38
Daily Costs ($) Including Overhead and Profit					
Material	n/a	n/a	n/a	n/a	n/a
Labor	1 Labor Foreman	2 Laborers	1 Equip. Oper. (light)	1 Equip. Oper. (medium)	Total
	489.60	930.40	594.80	618.40	2633.20
Equipment	1 Backhoe Loader, 48 H.P	1 Hyd. Hammer, (1200 lb)	1 F.E. Loader, W.M. 4 C.Y.	1 Pvmt. Rem. Bucket	Total
	401.94	197.56	727.98	63.14	1390.62
Production Efficiency of 5 days per week					
Hours/day	1st week	2nd week	3rd week	4th week	Payroll
10	100%	95%	90%	85%	120.0%

The new agency costs and time savings for Mill & Fill HMA activities are shown in Table 45. Since user time costs, user fuel costs, user safety costs, and user emissions are proportional to the lane closure days, the economic, social, and environmental impacts of accelerated construction strategy can be calculated once the time-savings are known. Therefore, the overall impacts of normal and accelerated construction strategies from a triple bottom line perspective are listed in Table 46 along with the cost savings with a discount rate of 4% and environmental impact reductions. By accelerating the milling process, an overall life cycle cost saving of approximately $294,000 is achieved, as well as reductions in user environmental impacts by 8% in three major categories. It is worth noting that agency environmental impacts are the same for both strategies, as it is assumed that over-time working does not affect the total quantities of materials processed or the total hours of equipment operations.

Table 45 Normal and Accelerated Scenarios for Mill & Fill HMA Activities

Mill & Fill HMA for 2”						
Strategy	Efficiency	Daily Production	Cost ($/sy)	Milling (K$/ln)	Total (K$/ln)	Time Saving
Normal	100%	690 sy	5.85	41.2	136.6	2 Weekdays
Accelerated	97.5%	841 sy	6.76	47.6	143.0	
Mill & Fill HMA for 4”						
Strategy	Efficiency	Daily Production	Cost ($/sy)	Milling (K$/ln)	Total (K$/ln)	Time Saving
Normal	100%	420 sy	9.55	100.8	358.5	4 Weekdays
Accelerated	95%	486 sy	11.40	120.5	378.1	

Table 46 Normal and Accelerated Scenario Life Cycle Costs and Environmental Impacts

Strategy	Life Cycle Costs (K$) with 4% Discount Rate					
	Agency	User				Grand Total
		Time	Fuel	Safety	User Total	
Normal	1376	3107	52	483	3642	5017
Accelerated	1445	2794	47	437	3279	4723
Cost Savings	-69	313	5	46	363	294
Strategy	Environmental Impacts					
	CO_2_E(kg)		Fossil Energy (MJ)		Total Energy(MJ)	
	Agency	User	Agency	User	Agency	User
Normal	1.21E+06	7.55E+05	4.01E+07	1.67E+07	4.03E+07	1.81E+07
Accelerated	1.21E+06	6.95E+05	4.01E+07	1.54E+07	4.03E+07	1.67E+07
Reductions	n/a	8.04%	n/a	8.05%	n/a	8.04%

5.4.2 Innovative Compaction with Verified Schedule Reduction

As discussed previously, in the LCA-LCCA model the “IC” alternative differs from “Traditional” only by the estimated service lives of rehabilitation activities. Meanwhile, one respondent of the survey by Salman et al. (2017) reported that paving processes using IC are 20% shorter than conventional ones. If this benefit were to be further verified, the framework could be utilized to estimate the potential economic, social, and environmental impacts.

The benefits of schedule reduction by using IC are reflected by a 20% reduction of duration of paving process and another 20% reduction of equipment costs. The costs associated with materials and labor remain constant. The original data from RSMeans and calculated values based on 20% reduction for labor and equipment costs are summarized in Table 47, where:

$$Adjusted\ Total\ Incl\ O\&P = \frac{Material + Labor + Equipment * 80\%}{Bare\ Total} \times Total\ Incl\ O\&P \qquad (9)$$

Table 47 Unit Costs and Time Savings of IC with Verified Shortened Schedule

Cost Code	32 12 16.13 0120 and 32 12 16.13 0380					
Activity	Plant-Mix Asphalt Paving					Crew B-25
Unit Costs ($/SY) Including Overhead and Profit						
HMA Paving for 2” Binder Course						
Material	Labor	Equipment	Bare Total	Total Incl O&P	Adjusted Total Incl O&P	Time Saving per lane
7.45	0.58	0.44	8.47	9.55	9.45	0.22 d
HMA Paving for 2” Wearing Course						
Material	Labor	Equipment	Bare Total	Total Incl O&P	Adjusted Total Incl O&P	Time Saving per lane
8.35	0.64	0.48	9.47	10.70	10.59	0.22 d

To reflect the time-savings in the rehabilitation schedule, the durations of activities Mill and Fill of 2” and 4” are both shortened by 1 weekday. Then the user cost items are calculated using the same approach.

Regarding agency environmental impacts, the emissions and energy consumption associated with equipment operations are reduced by 20% while the rest remains the same. Similar to other scenarios, user environmental impacts are directly related to the total duration of MRR activities throughout the analysis period. Equipment-related life cycle environmental impacts of paving the wearing or binder course, based on results from Athena Pavement LCA, are listed in Table 48. Therefore, the agency life cycle environmental impacts of IC with 20% shortened schedule can be calculated by subtracting 20% of the total equipment environmental impacts over the life cycle from the overall life cycle environmental impact of the "IC" alternatives. The overall impacts of "IC" alternative with verified shortened schedule are summarized in Table 49 and cost savings and environmental impact reductions are calculated.

Table 48 Environmental Impacts of Paving Equipment

Equipment Environmental Impacts for Paving one lane-mile 2" Wearing or Binder Course from Athena Pavement LCA		
CO$_2$_E(kg)	Fossil Energy (MJ)	Total Energy(MJ)
5.98E+04	8.67E+05	8.69E+05

Table 49 Overall Impact of IC Alternative with Verified Shortened Schedule

Strategy	Life Cycle Costs (K$) with 4% Discount Rate					
	Agency	User				Grand Total
		Time	Fuel	Safety	User Total	
Traditional	1376	3107	52	483	3642	5017
IC Verified	1321	2827	47	435	3309	4628
Cost Savings	55	280	5	48	333	389
Strategy	Environmental Impacts per Lane-Mile					
	CO$_2$_E(kg)		Fossil Energy (MJ)		Total Energy(MJ)	
	Agency	User	Agency	User	Agency	User
Traditional	1.21E+06	7.55E+05	4.01E+07	1.67E+07	4.03E+07	1.81E+07
IC Verified	9.75E+05	7.35E+05	3.38E+07	1.63E+07	3.41E+07	1.77E+07
Reductions	2.28E+05	1.91E+04	6.25E+06	4.20E+05	6.25E+06	4.55E+05
% Reductions	18.9%	2.5%	15.5%	2.5%	15.5%	2.5%

In the case of using IC with 20% shortened schedule, a life cycle cost saving of $395,000, 15.5% to 18.9% reductions in agency environmental impacts, and 2.5% reductions in user environmental impacts are expected. These results show good potential of IC as an improvement to conventional asphalt paving processes if accelerated paving can be achieved and the extra costs of using IC instruments stay at approximately 3% of the total cost.

5.5 Application of LCA and LCCA Results in Agency Decision-Making

Based on the specific goals and objectives regarding incorporating sustainability in the agency's transportation infrastructure asset management plans, public agencies using this decision support framework can evaluate these results and make informed decisions on whether non-traditional techniques or accelerated construction strategies should be implemented or not.

To balance agency costs with user costs, Salem and Genaidy (2007) reported that user costs are capped at 10% of agency costs in Indiana and at 50% to 75% of agency costs in New Jersey. For the accelerated construction strategy case shown in Table 46, the Indiana approach would discount the user cost saving to $36,300, which cannot offset additional agency cost of $69,000. However, the New Jersey approach would consider the user cost saving of $363,000 to be between $181,500 and $272,250, outweighing the additional agency cost. Therefore, the criteria that agencies use regarding agency costs versus user costs make a great difference and should be carefully selected.

Regarding LCA results of life cycle environmental impacts, public agencies may refer to their sustainability goals, objectives, and performance measures, and take environmental impact reduction into consideration in the decision-making process. Some commonly used approaches include:

- Using life cycle environmental impact reduction results as inputs for sustainability rating systems. For example, “reduce energy consumption”, “reduce greenhouse gas emissions”, and “reduce air pollutant emissions” are among the 60 criteria of ENVISION. The results from the LCA-LCCA model can be directly used to determine the level of achievement for the proposed projects based on the magnitude of life cycle environmental impact reductions.
- Assigning monetary values to environmental impact reductions to incorporate these values into project life cycle costs, and
- Considering environmental impact reductions as certain criteria in MCDM methods to make project recommendations.

Public agencies need to decide on the approach and weighting scheme that is most appropriate to their missions, goals, and objectives. In the case of IC with 20% shortened schedule, if one of the agency goals is to reduce its greenhouse gas emissions by at least 10% before 2050, then the implementation of IC should receive high priority in future roadway MRR projects for its potential of an 18.9% reduction in greenhouse gas emissions, while techniques such as WMA overlay may not deliver comparable performance in greenhouse gas emission reductions.

6 DISCUSSION, CONCLUSIONS, AND VALIDATION

6.1 Discussion

For the decision flowcharts, due to the purpose of identifying the applicable MRR techniques, the proposed decision flowcharts have covered mostly technical factors instead of economic or environmental factors. The adoption of these decision flowcharts is highly recommended unless equivalent tools involving non-traditional techniques are currently being used by public agencies.

For the MCDM model, while it allows customization through the user-specified weighting scheme, public agencies also need to exercise caution in defining their own weights in order to ensure the effectiveness of the results. Rather than deliberately assigning weights that lead to desired end results, agencies are encouraged to develop the priorities according to their actual sustainability goals and objectives.

For the LCA-LCCA model, the development of IC project alternative considers extended estimated service lives as the only benefit for IC application because there is a lack of supporting data for other assumed benefits. Once the practice of IC becomes more widespread, this project alternative may be revisited.

In addition, the user LCA model has simplified certain conditions such as traffic patterns, traffic management plans, and link speeds to avoid further complication in the modeling. The evaluation of environmental impacts of additional crashes is not included in the model due to the limitation of available tools.

For LCCA, a number of MRR activity cost entries are generated from the survey results by Salman et al. (2017). Therefore, the accuracy of LCCA results largely depends on the quality of responses. Due to relatively small sample sizes, the cost information for CIR, FDR, and IC activities may not be a just reflection of the typical performance on a national level. The salvage values for project alternatives at the end of 60-year analysis period are not included in the LCCA results because of the controversy in determining the actual values of constructed pavement sections as well as the negligible influence (less than 1%) of salvage values on the final results due to a relatively long analysis period. Should the salvage values be calculated using the remaining portion of the latest investments at year 60 and included in the final results, the “FDR” and “IC” alternatives would have even greater cost savings because of higher salvage values.

Considering the advancement of technologies and the emergence of innovations in public transit, renewable energy-based vehicles, autonomous vehicles, new materials, and other relevant fields, the parameters such as construction energy consumption and vehicle emission rates used in the LCA-LCCA model are subject to change. This could potentially reduce the overall life cycle environmental impacts because of lower agency and/or user emissions and energy consumption. Meanwhile, some non-traditional techniques that have not yet been widely adopted on a national level, such as FDR and IC, may achieve greater life cycle environmental impact reductions in the future after the construction proficiency increases.

6.2 Conclusions

This research is expected to fill the gap of a comprehensive project-level roadway infrastructure management framework following the triple bottom line of sustainability and to provide suggestions to public agencies on project-level decision-making.

The proposed infrastructure management framework will assist transportation agencies in (1) developing roadway MRR project alternatives, (2) evaluating project alternatives based on multiple criteria, and (3) determining the life cycle economic, social, and environmental impacts of project alternatives to make informed project-level decisions. Agencies can also make adjustments to the decision flowcharts, the MCDM model, and the LCA-LCCA model based on changing demands to maximize the benefits of using this framework.

The decision flowcharts and the MCDM model are developed to assist users to expand their scope of consideration beyond agency costs so that decisions are made in a more holistic manner. The LCA-LCCA model allows users to quantify the life cycle economic, social, and environmental impacts of different project alternatives, and perform what-if scenario analysis including the evaluation of accelerated strategies to make project decisions that minimize the overall life cycle impacts. The results of life cycle environmental impacts from the LCA-LCCA model can also serve as inputs to sustainability rating systems such as ENVISION to evaluate and promote sustainability practices in roadway infrastructure asset management.

Based on the demonstration analysis of interstate roadway MRR project alternatives, for flexible pavements using traditional Mill and Fill alternative as the benchmark, project alternatives that involve asphalt “Recycling” (including HIPR), “CIR”, and “FDR” result in considerably lower life cycle costs (by 34~39%) and life cycle environmental impacts (by 34~53%); “WMA” alternative delivers comparable life cycle costs and minimum life cycle environmental impact reductions (less than 2%); and “IC” alternative has slightly lower life cycle costs (by 6%) and life cycle environmental impacts (9~10%). For rigid pavement project alternatives, using precast concrete slabs results in slightly lower life cycle economic and social impacts (by 2%) and considerably lower life cycle environmental impacts (by 22~24%) compared to using traditional cast-in-place concrete.

6.3 Validation

The validation of this research has been conducted through a combination of expert opinions and literature contrast as follows:

- The decision flowcharts and the MCDM model have been reviewed by NYSDOT officials with feedback provided and included in Appendix VIII. Necessary changes have already been made accordingly.
- The results of the LCA-LCCA models are in good consistency with the findings of Zhang (2009) regarding user LCCA, PB Americas, Inc. et al. (2013) regarding agency LCA of warm mix asphalt, and Cross et al. (2010) regarding agency LCA and LCCA of cold in-place recycling.

To further validate the framework, collaboration with public agencies is needed for the implementation of this framework and the evaluation of project sustainability performance.

7 RECOMMENDATIONS FOR FUTURE STUDIES

Future studies can focus on the following aspects while balancing the comprehensiveness of the framework and the ease of implementation:

- Expand the flowchart and the MCDM model to include additional criteria such as safety, durability, and public perception.
- Enhance the LCA-LCCA model by investigating different roadway types (e.g. local and state roads), pavement types (e.g. composite pavement), vehicle types (e.g. electric vehicles), fuel types (e.g. biodiesel), and traffic management plans (e.g. detour).
- Evaluate environmental impacts of additional crash events due to lane closure through traffic micro-simulation tools.
- Include elements from other sustainability triple bottom line categories such as noise, local development, and wild-life impacts in the LCA-LCCA model.
- Utilize probabilistic data to generate results that reflect risk.

APPENDIX I: Questionnaire to State DOTs on Innovative MRR Techniques of Asphalt Roadways by Salman et al. (2017)

QUESTIONNAIRE

Innovative Techniques for Maintenance, Repair, and Reconstruction (MRR) of Asphalt Roadways

The Civil and Environmental Engineering Department at Syracuse University, is conducting a research study that is funded by the University Transportation Research Center (Region 2) to study potential ***innovative techniques for maintenance, repair, and reconstruction (MRR) of asphalt roadways****. More specifically, the research team is investigating innovative techniques that differ from the traditional techniques mainly in terms of reduced project duration, reduced energy requirements (environmentally friendly), and reduced direst and user costs. The research team generated the following questionnaire to gain an understanding with regards to the current state of practice at State Departments of Transportation in relation to asphalt roadway techniques and the factors that play an important role in the decision-making process. There are 10 questions in this survey and the research team estimates it will take 20 minutes to complete.*

If you have additional comments, please feel free to add them at the end of the survey.

We would like to thank you in advance for your participation in this survey. Your response will be invaluable in achieving the objectives of the study.

Respondent's Contact Information:

Name:

Current Position / Title:

Agency:

Address:

Phone Number:

Email:

May we contact you with follow up questions? Yes No

1. Please indicate which of the following traditional maintenance, repair, and reconstruction (MRR) methods your agency has used for asphalt roadways in the last five years.

a. Chip Seal [ ]
b. Crack Seal [ ]
c. Hot Mix Asphalt Overlay [ ]
d. Scrub Seal [ ]
e. Slurry Seal [ ]
f. Total Reconstruction [ ]
g. Other (Please specify) [ ]

2. Please indicate how extensively the following traditional maintenance, repair, and reconstruction (MRR) methods have been used by your agency in the last five years.

MRR Method	Average miles/year
Chip Seal	
Crack Seal	
Scrub Seal	
Slurry Seal	
Hot Mix Asphalt Overlay	
Total Reconstruction	
Other	

3. Please indicate which of the following innovative MRR methods your agency has used for asphalt roadways in the last five years:

a. Warm Mix Asphalt Overlay [ ]
b. Asphalt Full Depth Reclamation [ ]
c. Asphalt Partial Depth Reclamation [ ]
d. Reclaimed Asphalt Pavement (RAP) [ ]
e. Cold In Place Recycling [ ]
f. Intelligent Compaction [ ]
g. Innovative Soil Stabilization* [ ]
h. Other (Please specify) [ ]
i. The agency has not used innovative methods [ ]

**Examples of innovative sol stabilization techniques include use of geosynthetics, geogrid reinforcements, and nontraditional additives.*

4. Does your agency plan to undertake any pilot projects that feature innovative maintenance, repair, and reconstruction methods for asphalt roadways in the near future? If yes, please elaborate on the planned projects:

a. Yes [ ]
b. No [ ]

Planned projects:

5a. If your agency has **only** used traditional techniques in the last five years and does **not** plan to use innovative methods in the near future, please provide a brief list of potential reasons as to why the agency does not utilize innovative techniques (*The rest of the survey focuses on innovative methods; therefore, this will serve as the last question for your agency).*

a. Lack of familiarity [ ]
b. Lack of experienced contractors in the region [ ]
c. Lack of regulations/design standards [ ]
d. Other(s): Please specify [ ]

5b. If your agency **has used** innovative techniques (in combination with or without traditional methods), for each of the innovative methods used please provide information regarding how extensively these methods are used (average miles/year), cost, expected service life, and construction time.

MRR Method	**Average miles/year**	**Cost**	**Expected Service Life**	**Construction Time**
Warm Mix Asphalt Overlay				
Asphalt Full Depth Reclamation				
Asphalt Partial Depth Reclamation				
Reclaimed Asphalt Pavement (RAP)				
Cold In Place Recycling				
Intelligent Compaction				
Innovative Soil Stabilization				
Other (Please specify)				

6. Please specify the percentage of innovative MRR projects your agency has completed that were:

a. On or ahead of schedule [ ]
b. Within or below budget [ ]
c. With acceptable quality and workmanship [ ]
d. With no accidents [ ]

7. Please rate the importance of the following factors in the decision-making process to determine whether innovative MRR techniques should be utilized. A value of “1” represents not important and a value of “5” represents very important.

Factors	Rating
Initial Construction Cost	1 2 3 4 5
Life Cycle Costs	1 2 3 4 5
Amount of Virgin Materials Used	1 2 3 4 5
Condition of the Existing Road	1 2 3 4 5
Greenhouse gas emissions (from construction equipment)	1 2 3 4 5
Construction Schedule	1 2 3 4 5
Lane Closures	1 2 3 4 5
Traffic delays	1 2 3 4 5
Greenhouse gas emissions from users	1 2 3 4 5
Fuel consumption of users	1 2 3 4 5
Others (Please specify):	1 2 3 4 5

8. If your agency had MRR projects involving use of Reclaimed Asphalt Pavement (RAP), what percentage of RAP has been used in these projects?

a. 0-5% [ ]
b. 6-10% [ ]
c. 11-15% [ ]
d. 16-20% [ ]
e. 21-25% [ ]
f. 26% or greater [ ]

If your agency has used a higher percentage of RAP than 26%, please indicate what percentage was used and provide details of the project where it was used.

9. Comment on the challenges your agency has faced employing an innovative technique.

MRR Method	Challenges
Warm Mix Asphalt Overlay	
Asphalt Full Depth Reclamation	
Asphalt Partial Depth Reclamation	
Reclaimed Asphalt Pavement (RAP)	
Cold In Place Recycling	
Intelligent Compaction	
Innovative Soil Stabilization	
Other (Please specify)	

10. Does your agency utilize a decision support system (DSS) to determine the type of maintenance, repair, or reconstruction method that should be used on a particular asphalt roadway? If yes, please elaborate on this system in the space provided below:

a. Yes [ ]
b. No [ ]

APPENDIX II: Rehabilitation Schedules and Agency Costs of Alternatives

Flexible Pavement:

“Traditional” Rehabilitation Schedule

Year	Service Life	MRR Activity	Detail	Cost/LN(K$)
0	15	M&F HMA	4" (2" wearing + 2" binder)	358.5
3	3	Crack Seal	1000 ft/ln-mile	2.2
6	4	Crack Seal	3750 ft/ln-mile	8.3
10	8	Patch	2% Lane area	13.8
15	9	M&F HMA	2" wearing course, no shoulder	136.6
21	8	Patch	3% Lane area	21.1
24	15	M&F HMA	4" (2" wearing + 2" binder)	358.5
27	3	Crack Seal	1500 ft/ln-mile	3.3
30	4	Crack Seal	4500 ft/ln-mile	10.0
34	8	Patch	2% Lane area	13.8
39	9	M&F HMA	2" wearing course, no shoulder	136.6
45	8	Patch	3% Lane area	21.1
48	15	M&F HMA	4" (2" wearing + 2" binder)	358.5
51	3	Crack Seal	1500 ft/ln-mile	3.3
54	4	Crack Seal	4500 ft/ln-mile	10
58	8	Patch	2% Lane area	13.8

“Recycling” Rehabilitation Schedule

Year	Service Life	MRR Activity	Detail	Cost/LN(K$)
0	15	HIPR	4" (2" wearing + 2" binder)	268.8
3	3	Crack Seal	1000 ft/ln-mile	2.2
6	4	Crack Seal	3750 ft/ln-mile	8.3
10	8	Patch	2% Lane area	13.8
15	9	M&F HMA	2" wearing course, no shoulder	136.6
21	8	Patch	3% Lane area	21.1
24	15	HIPR	4" (2" wearing + 2" binder)	268.8
27	3	Crack Seal	1500 ft/ln-mile	3.3
30	4	Crack Seal	4500 ft/ln-mile	10.0
34	8	Patch	2% Lane area	13.8
39	9	M&F HMA	2" wearing course, no shoulder	136.6
45	8	Patch	3% Lane area	21.1
48	15	HIPR	4" (2" wearing + 2" binder)	268.8
51	3	Crack Seal	1500 ft/ln-mile	3.3
54	4	Crack Seal	4500 ft/ln-mile	10.0
58	8	Patch	2% Lane area	13.8

“WMA” Rehabilitation Schedule

Year	Service Life	MRR Activity	Detail	Cost/LN(K$)
0	15	M&F WMA	4" (2" wearing + 2" binder)	341.0
3	3	Crack Seal	1000 ft/ln-mile	2.2
6	4	Crack Seal	3750 ft/ln-mile	8.3
10	8	Patch	2% Lane area	13.8
15	9	M&F WMA	2" wearing course, no shoulder	130.4
21	8	Patch	3% Lane area	21.1
24	15	M&F WMA	4" (2" wearing + 2" binder)	341.0
27	3	Crack Seal	1500 ft/ln-mile	3.3
30	4	Crack Seal	4500 ft/ln-mile	10.0
34	8	Patch	2% Lane area	13.8
39	9	M&F WMA	2" wearing course, no shoulder	130.4
45	8	Patch	3% Lane area	21.1
48	15	M&F WMA	4" (2" wearing + 2" binder)	341.0
51	3	Crack Seal	1500 ft/ln-mile	3.3
54	4	Crack Seal	4500 ft/ln-mile	10
58	8	Patch	2% Lane area	13.8

“CIR” Rehabilitation Schedule

Year	Service Life	MRR Activity	Detail	Cost/LN(K$)
0	15	CIR	4" (2" wearing + 2" binder)	271.2
3	3	Crack Seal	1000 ft/ln-mile	2.2
6	4	Crack Seal	3750 ft/ln-mile	8.3
10	8	Patch	2% Lane area	13.8
15	9	M&F HMA	2" wearing course, no shoulder	136.6
21	8	Patch	3% Lane area	21.1
24	15	CIR	4" (2" wearing + 2" binder)	271.2
27	3	Crack Seal	1500 ft/ln-mile	3.3
30	4	Crack Seal	4500 ft/ln-mile	10.0
34	8	Patch	2% Lane area	13.8
39	9	M&F HMA	2" wearing course, no shoulder	136.6
45	8	Patch	3% Lane area	21.1
48	15	CIR	4" (2" wearing + 2" binder)	271.2
51	3	Crack Seal	1500 ft/ln-mile	3.3
54	4	Crack Seal	4500 ft/ln-mile	10
58	8	Patch	2% Lane area	13.8

“FDR” Rehabilitation Schedule				
Year	**Service Life**	**MRR Activity**	**Detail**	**Cost/LN(K$)**
0	15	FDR	4" (2" wearing + 2" binder)	369.5
5	3	Crack Seal	1000 ft/ln-mile	2.2
8	4	Crack Seal	3750 ft/ln-mile	8.3
12	8	Patch	2% Lane area	13.8
18	9	M&F HMA	2" wearing course, no shoulder	136.6
24	8	Patch	3% Lane area	21.1
27	15	FDR	4" (2" wearing + 2" binder)	369.5
32	3	Crack Seal	1500 ft/ln-mile	3.3
35	4	Crack Seal	4500 ft/ln-mile	10.0
39	8	Patch	2% Lane area	13.8
45	9	M&F HMA	2" wearing course, no shoulder	136.6
51	8	Patch	3% Lane area	21.1
54	15	FDR	4" (2" wearing + 2" binder)	369.5
59	3	Crack Seal	1500 ft/ln-mile	3.3

“IC” Rehabilitation Schedule				
Year	**Service Life**	**MRR Activity**	**Detail**	**Cost/LN(K$)**
0	15	M&F HMA with IC	4" (2" wearing + 2" binder)	369.2
4	3	Crack Seal	1000 ft/ln-mile	2.2
7	4	Crack Seal	3750 ft/ln-mile	8.3
11	8	Patch	2% Lane area	13.8
17	9	M&F HMA with IC	2" wearing course, no shoulder	140.7
23	8	Patch	3% Lane area	21.1
27	15	M&F HMA with IC	4" (2" wearing + 2" binder)	369.2
31	3	Crack Seal	1500 ft/ln-mile	3.3
34	4	Crack Seal	4500 ft/ln-mile	10.0
38	8	Patch	2% Lane area	13.8
44	9	M&F HMA with IC	2" wearing course, no shoulder	140.7
50	8	Patch	3% Lane area	21.1
54	15	M&F HMA with IC	4" (2" wearing + 2" binder)	369.2
58	3	Crack Seal	1500 ft/ln-mile	3.3

Rigid Pavement:

“CIP” Rehabilitation Schedule				
Year	**Service Life**	**MRR Activity**	**Detail**	**Cost/LN(K$)**
0	15	Joint Seal	6600 ft/ln-mile	11.7
0	15	Partial Depth Repair	5% Lane area	48.8
0	15	Full Depth Repair	15% Lane area	200.8
0	15	Diamond Grinding	0.2" 100% Lane area	49.0
15	13	Joint Seal	4400 ft/ln-mile	7.8
15	13	Partial Depth Repair	2% Lane area	19.5
28	15	Joint Seal	6600 ft/ln-mile	11.7
28	15	Partial Depth Repair	5% Lane area	48.8
28	15	Full Depth Repair	10% Lane area	133.9
28	15	Diamond Grinding	0.2" 100% Lane area	49.0
43	13	Joint Seal	4400 ft/ln-mile	7.8
43	13	Partial Depth Repair	2% Lane area	19.5
56	15	Joint Seal	6600 ft/ln-mile	11.7
56	15	Partial Depth Repair	5% Lane area	48.8
56	15	Full Depth Repair	15% Lane area	200.8
56	15	Diamond Grinding	0.2" 100% Lane area	49.0

“PCP” Rehabilitation Schedule				
Year	**Service Life**	**MRR Activity**	**Detail**	**Cost/LN(K$)**
0	15	Joint Seal	6600 ft/ln-mile	11.7
0	15	Partial Depth Repair	5% Lane area	48.8
0	15	Full Depth Repair with PCP	15% Lane area	442.8
0	15	Diamond Grinding	0.2" 100% Lane area	49.0
15	13	Joint Seal	4400 ft/ln-mile	7.8
15	13	Partial Depth Repair	2% Lane area	19.5
28	15	Joint Seal	6600 ft/ln-mile	11.7
28	15	Partial Depth Repair	5% Lane area	48.8
28	15	Full Depth Repair with PCP	10% Lane area	295.2
28	15	Diamond Grinding	0.2" 100% Lane area	49.0
43	13	Joint Seal	4400 ft/ln-mile	11.7
43	13	Partial Depth Repair	2% Lane area	19.5
56	15	Joint Seal	6600 ft/ln-mile	11.7
56	15	Partial Depth Repair	5% Lane area	48.8
56	15	Full Depth Repair with PCP	15% Lane area	442.8
56	15	Diamond Grinding	0.2" 100% Lane area	49.0

APPENDIX III: Agency LCA Results Per Lane from Athena Pavement LCA

Alternatives	Global Warming Potential	Total Primary Energy	Non-Renewable Energy
	kg CO2 E / Lane	MJ / Lane	MJ / Lane
Traditional	1.21E+06	4.03E+07	4.02E+07
Recycling	8.50E+05	2.65E+07	2.64E+07
WMA	1.17E+06	3.99E+07	3.98E+07
CIR	5.00E+05	2.13E+07	2.13E+07
FDR	4.64E+05	1.93E+07	1.93E+07
IC	1.05E+06	3.52E+07	3.51E+07
CIP	3.64E+05	3.72E+06	3.66E+06
PCP	3.13E+05	3.20E+06	3.16E+06

Alternatives	Fossil Fuel Consumption	Acidification Potential	Ozone Depletion Potential
	MJ / Lane	kg SO2 E / Lane	kg CFC -11 E / Lane
Traditional	4.00E+07	9.43E+03	3.41E-05
Recycling	2.63E+07	6.78E+03	2.48E-05
WMA	3.96E+07	9.30E+03	3.33E-05
CIR	2.11E+07	3.64E+03	1.27E-05
FDR	1.92E+07	3.40E+03	1.19E-05
IC	3.50E+07	8.23E+03	2.98E-05
CIP	3.56E+06	2.05E+03	4.75E-03
PCP	3.08E+06	1.79E+03	4.75E-03

Alternatives	HH Criteria	Eutrophication Potential	Smog Potential
	kg PM2.5 / Lane	kg N E / Lane	kg O3 E / Lane
Traditional	1.05E+03	5.92E+02	2.58E+05
Recycling	6.98E+02	4.30E+02	1.92E+05
WMA	1.04E+03	5.89E+02	2.57E+05
CIR	5.10E+02	2.22E+02	8.68E+04
FDR	4.66E+02	2.09E+02	8.27E+04
IC	9.12E+02	5.17E+02	2.26E+05
CIP	2.77E+02	3.17E+02	6.09E+04
PCP	2.38E+02	2.76E+02	5.49E+04

APPENDIX IV: Vehicle Operation Mode Distribution for MOVES

MOVES opMode		Scenarios														
		Regular			MRR											
					LOS - ABC			LOS - D			LOS - E			LOS - F		
ID	Name	U	W	D	U	W	D	U	W	D	U	W	D	U	W	D
0	Braking	0.024	0.024	0.024	0.024	0.08	0.024	0.05	0.08	0.024	0.105	0.08	0.024	0.138	0.08	0.024
1	Idling	0	0	0	0	0	0	0	0	0	0	0	0	0.012	0	0
11	Low Speed Coasting; VSP< 0; 1<=Speed<25	0	0	0	0	0.003	0	0	0.003	0	0.016	0.003	0	0.288	0.003	0
12	Cruise/Acceleration; 0<=VSP< 3; 1<= Speed<25	0	0	0	0	0.004	0	0	0.004	0	0.013	0.004	0	0.332	0.004	0
13	Cruise/Acceleration; 3<=VSP< 6; 1<=Speed<25	0	0	0	0	0	0	0	0	0	0.008	0	0	0.11	0	0
14	Cruise/Acceleration; 6<=VSP< 9; 1<=Speed<25	0	0	0	0	0	0	0	0	0	0.003	0	0	0.041	0	0
15	Cruise/Acceleration; 9<=VSP<12; 1<=Speed<25	0	0	0	0	0	0	0	0	0	0.002	0	0	0.013	0	0
16	Cruise/Acceleration; 12<=VSP; 1<=Speed<25	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0	0
21	Moderate Speed Coasting; VSP< 0; 25<=Speed<50	0	0	0	0	0.167	0	0.01	0.167	0	0.222	0.167	0	0.018	0.167	0
22	Cruise/Acceleration; 0<=VSP< 3; 25<=Speed<50	0	0	0	0	0.111	0	0.006	0.111	0	0.151	0.111	0	0.004	0.111	0
23	Cruise/Acceleration; 3<=VSP< 6; 25<=Speed<50	0	0	0	0	0.148	0	0.008	0.148	0	0.153	0.148	0	0.001	0.148	0
24	Cruise/Acceleration; 6<=VSP< 9; 25<=Speed<50	0	0	0	0	0.106	0	0.008	0.106	0	0.138	0.106	0	0.002	0.106	0
25	Cruise/Acceleration; 9<=VSP<12; 25<=Speed<50	0	0	0	0	0.078	0	0.004	0.078	0	0.074	0.078	0	0.001	0.078	0
27	Cruise/Acceleration; 12<=VSP<18; 25<=Speed<50	0	0	0	0	0.095	0	0.003	0.095	0	0.058	0.095	0	0.001	0.095	0
28	Cruise/Acceleration; 18<=VSP<24; 25<=Speed<50	0	0	0	0	0.025	0	0.001	0.025	0	0.012	0.025	0	0	0.025	0
29	Cruise/Acceleration; 24<=VSP<30; 25<=Speed<50	0	0	0	0	0.007	0	0	0.007	0	0.004	0.007	0	0	0.007	0
30	Cruise/Acceleration; 30<=VSP; 25<=Speed<50	0	0	0	0	0.014	0	0.001	0.014	0	0.021	0.014	0	0.009	0.014	0
33	Cruise/Acceleration; VSP< 6; 50<=Speed	0.238	0.238	0.238	0.238	0.058	0.238	0.33	0.058	0.238	0.008	0.058	0.238	0	0.058	0.238
35	Cruise/Acceleration; 6<=VSP<12; 50<=Speed	0.337	0.337	0.337	0.337	0.046	0.337	0.315	0.046	0.337	0.003	0.046	0.337	0	0.046	0.337
37	Cruise/Acceleration; 12<=VSP<18; 50<=Speed	0.242	0.242	0.242	0.242	0.023	0.242	0.162	0.023	0.242	0.003	0.023	0.242	0	0.023	0.242
38	Cruise/Acceleration; 18<=VSP<24; 50<=Speed	0.1	0.1	0.1	0.1	0.016	0.1	0.051	0.016	0.1	0	0.016	0.1	0	0.016	0.1
39	Cruise/Acceleration; 24<=VSP<30; 50<=Speed	0.024	0.024	0.024	0.024	0.003	0.024	0.013	0.003	0.024	0	0.003	0.024	0	0.003	0.024
40	Cruise/Acceleration; 30<=VSP; 50<=Speed	0.035	0.035	0.035	0.035	0.016	0.035	0.038	0.016	0.035	0.006	0.016	0.035	0	0.016	0.035

Notes: U: Upstream Link; W: Work zone Link; D: Downstream Link

APPENDIX V: Overall LCA Results Per Lane

Environmental Impact: CO_2_E(kg)/Lane			
Alternatives	**Agency**	**User**	**Total**
Traditional	1.21E+06	7.57E+05	1.96E+06
Recycling	8.50E+05	4.33E+05	1.28E+06
WMA	1.17E+06	7.57E+05	1.93E+06
CIR	5.00E+05	4.33E+05	9.33E+05
FDR	4.64E+05	4.57E+05	9.21E+05
IC	1.05E+06	7.34E+05	1.79E+06
CIP	3.64E+05	5.12E+05	8.76E+05
PCP	3.13E+05	3.69E+05	6.82E+05

Environmental Impact: Fossil Energy (MJ) /Lane			
Alternatives	**Agency**	**User**	**Total**
Traditional	4.00E+07	1.67E+07	5.67E+07
Recycling	2.63E+07	9.54E+06	3.59E+07
WMA	3.96E+07	1.67E+07	5.63E+07
CIR	2.11E+07	9.54E+06	3.07E+07
FDR	1.92E+07	1.01E+07	2.92E+07
IC	3.50E+07	1.62E+07	5.11E+07
CIP	3.56E+06	1.13E+07	1.48E+07
PCP	3.08E+06	8.14E+06	1.12E+07

Environmental Impact: Total Energy (MJ) /Lane			
Alternatives	**Agency**	**User**	**Total**
Traditional	4.03E+07	1.81E+07	5.84E+07
Recycling	2.65E+07	1.03E+07	3.68E+07
WMA	3.99E+07	1.81E+07	5.79E+07
CIR	2.13E+07	1.03E+07	3.16E+07
FDR	1.93E+07	1.09E+07	3.02E+07
IC	3.52E+07	1.75E+07	5.27E+07
CIP	3.72E+06	1.22E+07	1.59E+07
PCP	3.20E+06	8.82E+06	1.20E+07

APPENDIX VI: Lane Closure Durations and User Costs of Alternatives Per Lane

Flexible Pavement:

"Traditional" Lane Closure and User Costs (K$/LN)						
Year	MRR Activity	Lane Closure Days		Time Delay Cost	Fuel Cost	Crash Cost
		Weekday	Weekend			
0	M&F HMA	37	14	743	12.4	109.7
3	Crack Seal	1	0	17	0.3	3.4
6	Crack Seal	3	0	50	0.8	10.0
10	Patch	3	0	50	0.8	10.0
15	M&F HMA	15	4	286	4.8	45.9
21	Patch	5	0	83	1.4	16.6
24	M&F HMA	37	14	743	12.4	109.7
27	Crack Seal	1	0	17	0.3	3.4
30	Crack Seal	3	0	50	0.8	10.0
34	Patch	3	0	50	0.8	10.0
39	M&F HMA	15	4	286	4.8	45.9
45	Patch	5	0	83	1.4	16.6
48	M&F HMA	37	14	743	12.4	109.7
51	Crack Seal	1	0	17	0.3	3.4
54	Crack Seal	3	0	50	0.8	10.0
58	Patch	3	0	50	0.8	10.0

"Recycling" Lane Closure and User Costs (K$/LN)						
Year	MRR Activity	Lane Closure Days		Time Delay Cost	Fuel Cost	Crash Cost
		Weekday	Weekend			
0	HIPR	14	4	269	4.5	42.8
3	Crack Seal	1	0	17	0.3	3.4
6	Crack Seal	3	0	50	0.8	10.0
10	Patch	3	0	50	0.8	10.0
15	M&F HMA	15	4	286	4.8	45.9
21	Patch	5	0	83	1.4	16.6
24	HIPR	14	4	269	4.5	42.8
27	Crack Seal	1	0	17	0.3	3.4
30	Crack Seal	3	0	50	0.8	10.0
34	Patch	3	0	50	0.8	10.0
39	M&F HMA	15	4	286	4.8	45.9
45	Patch	5	0	83	1.4	16.6
48	HIPR	14	4	269	4.5	42.8
51	Crack Seal	1	0	17	0.3	3.4
54	Crack Seal	3	0	50	0.8	10.0
58	Patch	3	0	50	0.8	10.0

“WMA” Lane Closure and User Costs (K$/LN)

Year	MRR Activity	Lane Closure Days		Time Delay Cost	Fuel Cost	Crash Cost
		Weekday	Weekend			
0	M&F WMA	37	14	743	12.4	109.7
3	Crack Seal	1	0	17	0.3	3.4
6	Crack Seal	3	0	50	0.8	10.0
10	Patch	3	0	50	0.8	10.0
15	M&F WMA	15	4	286	4.8	45.9
21	Patch	5	0	83	1.4	16.6
24	M&F WMA	37	14	743	12.4	109.7
27	Crack Seal	1	0	17	0.3	3.4
30	Crack Seal	3	0	50	0.8	10.0
34	Patch	3	0	50	0.8	10.0
39	M&F WMA	15	4	286	4.8	45.9
45	Patch	5	0	83	1.4	16.6
48	M&F WMA	37	14	743	12.4	109.7
51	Crack Seal	1	0	17	0.3	3.4
54	Crack Seal	3	0	50	0.8	10.0
58	Patch	3	0	50	0.8	10.0

“CIR” Lane Closure and User Costs (K$/LN)

Year	MRR Activity	Lane Closure Days		Time Delay Cost	Fuel Cost	Crash Cost
		Weekday	Weekend			
0	CIR	14	4	269	4.5	42.8
3	Crack Seal	1	0	17	0.3	3.4
6	Crack Seal	3	0	50	0.8	10.0
10	Patch	3	0	50	0.8	10.0
15	M&F WMA	15	4	286	4.8	45.9
21	Patch	5	0	83	1.4	16.6
24	CIR	14	4	269	4.5	42.8
27	Crack Seal	1	0	17	0.3	3.4
30	Crack Seal	3	0	50	0.8	10.0
34	Patch	3	0	50	0.8	10.0
39	M&F WMA	15	4	286	4.8	45.9
45	Patch	5	0	83	1.4	16.6
48	CIR	14	4	269	4.5	42.8
51	Crack Seal	1	0	17	0.3	3.4
54	Crack Seal	3	0	50	0.8	10.0
58	Patch	3	0	50	0.8	10.0

"FDR" Lane Closure and User Costs (K$/LN)						
Year	MRR Activity	Lane Closure Days		Time Delay Cost	Fuel Cost	Crash Cost
		Weekday	Weekend			
0	FDR	17	6	338	5.6	50.7
5	Crack Seal	1	0	17	0.3	3.4
8	Crack Seal	3	0	50	0.8	10.0
12	Patch	3	0	50	0.8	10.0
18	M&F WMA	15	4	286	4.8	45.9
24	Patch	5	0	83	1.4	16.6
27	FDR	17	6	338	5.6	50.7
32	Crack Seal	1	0	17	0.3	3.4
35	Crack Seal	3	0	50	0.8	10.0
39	Patch	3	0	50	0.8	10.0
45	M&F WMA	15	4	286	4.8	45.9
51	Patch	5	0	83	1.4	16.6
54	FDR	17	6	338	5.6	50.7
59	Crack Seal	1	0	17	0.3	3.4

"IC" Lane Closure and User Costs (K$/LN)						
Year	MRR Activity	Lane Closure Days		Time Delay Cost	Fuel Cost	Crash Cost
		Weekday	Weekend			
0	M&F HMA with IC	37	14	743	12.4	109.7
4	Crack Seal	1	0	17	0.3	3.4
7	Crack Seal	3	0	50	0.8	10.0
11	Patch	3	0	50	0.8	10.0
17	M&F HMA with IC	15	4	286	4.8	45.9
23	Patch	5	0	83	1.4	16.6
27	M&F HMA with IC	37	14	743	12.4	109.7
31	Crack Seal	1	0	17	0.3	3.4
34	Crack Seal	3	0	50	0.8	10.0
38	Patch	3	0	50	0.8	10.0
44	M&F HMA with IC	15	4	286	4.8	45.9
50	Patch	5	0	83	1.4	16.6
54	M&F HMA with IC	37	14	743	12.4	109.7
58	Crack Seal	1	0	17	0.3	3.4

Rigid Pavement:

"CIP" Lane Closure and User Costs (K$/LN)						
Year	**MRR Activity**	**Lane Closure Days**		**Time Delay Cost**	**Fuel Cost**	**Crash Cost**
		Weekday	**Weekend**			
0	Joint Seal	2	0	33	0.6	6.6
0	Partial Depth Repair	11	4	219	3.7	32.8
0	Full Depth Repair	16	6	321	5.4	47.6
0	Diamond Grinding	4	2	85	1.4	11.4
15	Joint Seal	2	0	33	0.6	6.6
15	Partial Depth Repair	6	2	118	2.0	17.9
28	Joint Seal	2	0	33	0.6	6.6
28	Partial Depth Repair	11	4	219	3.7	32.8
28	Full Depth Repair	15	4	286	4.8	45.9
28	Diamond Grinding	4	2	85	1.4	11.4
43	Joint Seal	2	0	33	0.6	6.6
43	Partial Depth Repair	6	2	118	2.0	17.9
56	Joint Seal	2	0	33	0.6	6.6
56	Partial Depth Repair	11	4	219	3.7	32.8
56	Full Depth Repair	16	6	321	5.4	47.6
56	Diamond Grinding	4	2	85	1.4	11.4

"PCP" Lane Closure and User Costs (K$/LN)						
Year	**MRR Activity**	**Lane Closure Days**		**Time Delay Cost**	**Fuel Cost**	**Crash Cost**
		Weekday	**Weekend**			
0	Joint Seal	2	0	33	0.6	6.6
0	Partial Depth Repair	11	4	219	3.7	32.8
0	Full Depth Repair with PCP	16	6	118	2.0	17.9
0	Diamond Grinding	4	2	85	1.4	11.4
15	Joint Seal	2	0	33	0.6	6.6
15	Partial Depth Repair	6	2	118	2.0	17.9
28	Joint Seal	2	0	33	0.6	6.6
28	Partial Depth Repair	11	4	219	3.7	32.8
28	Full Depth Repair with PCP	15	4	67	1.1	13.1
28	Diamond Grinding	4	2	85	1.4	11.4
43	Joint Seal	2	0	33	0.6	6.6
43	Partial Depth Repair	6	2	118	2.0	17.9
56	Joint Seal	2	0	33	0.6	6.6
56	Partial Depth Repair	11	4	219	3.7	32.8
56	Full Depth Repair with PCP	16	6	118	2.0	17.9
56	Diamond Grinding	4	2	85	1.4	11.4

APPENDIX VII: Daily Additional Crashes

Weekday Daily Additional Crashes					
Hour	Hourly Traffic	MRR v/c	Regular v/c	Change in Crash Rate	Change in Crash / 100 MVMT
1	316	0.16	0.08	-30.06	-9493
2	201	0.10	0.05	-21.27	-4272
3	162	0.08	0.04	-17.74	-2873
4	149	0.08	0.04	-16.54	-2472
5	224	0.11	0.06	-23.24	-5204
6	592	0.30	0.15	-41.13	-24353
7	1471	0.74	0.37	18.36	27016
8	2230	1.07	0.56	151.38	337564
9	1948	0.97	0.49	105.16	204813
10	1610	0.81	0.41	40.89	65833
11	1599	0.81	0.40	38.93	62239
12	1741	0.83	0.44	49.65	86436
13	1846	0.88	0.47	68.25	125976
14	1858	0.89	0.47	70.55	131098
15	1993	0.98	0.50	110.45	220178
16	2274	1.09	0.57	162.30	368996
17	2465	1.18	0.62	213.83	527001
18	2479	1.19	0.63	218.04	540588
19	1914	0.96	0.48	101.24	193795
20	1421	0.72	0.36	11.10	15781
21	1135	0.57	0.29	-21.43	-24318
22	1019	0.51	0.26	-30.25	-30821
23	799	0.40	0.20	-40.10	-32027
24	573	0.29	0.14	-40.82	-23407
Total					2748073

Weekend Daily Additional Crashes					
Hour	Hourly Traffic	MRR v/c	Regular v/c	Change in Crash Rate	Change in Crash / 100 MVMT
1	268	0.27	0.14	-69.60	-37294
2	180	0.18	0.09	-53.96	-19446
3	137	0.14	0.07	-43.66	-11949
4	94	0.09	0.05	-31.66	-5921
5	85	0.09	0.04	-29.21	-4984
6	129	0.13	0.07	-41.68	-10773
7	230	0.23	0.12	-63.69	-29287
8	334	0.34	0.17	-76.83	-51402
9	454	0.46	0.23	-79.76	-72410
10	593	0.60	0.30	-66.89	-79349
11	717	0.72	0.36	-40.72	-58389
12	812	0.82	0.41	-11.26	-18277
13	890	0.85	0.45	5.78	10280
14	892	0.85	0.45	6.52	11638
15	895	0.86	0.45	7.55	13514
16	898	0.86	0.45	8.82	15849
17	888	0.85	0.45	5.01	8894
18	847	0.81	0.43	-8.67	-14690
19	771	0.78	0.39	-25.06	-38621
20	645	0.65	0.33	-57.64	-74343
21	535	0.54	0.27	-74.42	-79593
22	474	0.48	0.24	-78.96	-74928
23	402	0.41	0.2	-80.07	-64345
24	307	0.31	0.15	-74.28	-45536
Total					-731364

APPENDIX VIII: Summary of Meeting Minutes at NYSDOT

Date and Time:

July, 10th, 2017 at 10:00 am

Location:

NYSDOT Main Office

50 Wolf Road

Albany, NY 12232

Attendees:

FHWA: Timothy LaCoss

NYSDOT: Thomas Kane, Russell Thielke, Benedikt Gustafsson, and Sigrid Rantanen

Syracuse University: Baris Salman, Song He, Kirill Skorokhod.

- Feedback on Proposed Decision Flowchart
    - State DOTs usually have their own and perhaps more detailed in-house decision flowchart/tree/matrices; and it is usually hard to justify the switch to the proposed flowchart. In NYSDOT, for example, a comprehensive pavement design manual, which provides recommendations of multiple alternatives for each distress type, is being used.
    - The phrase "recycling requirement" needs to be revisited to eliminate potential confusions.
    - Based on the practices in New York State, a condition can be added for the Cold-In-Place Recycling (CIR) method. In order to use this technique, the thickness of the existing pavement layer needs to be at least 4 inches.

  - The decision-making flow chart leads to only one alternative. Thus, it may not work well with the Excel based decision tool, as it requires at least two alternatives.
- Feedback on Proposed MCDM Modeling Tool
  - It is difficult to evaluate the “contractor expertise” criterion as it involves many different aspects and it is subject to high subjectivity. In many cases, the agency does not know which contracting company will be awarded with the project. “Contractor availability” can be a better criterion.
  - A new criterion can be added to the decision-making tool to capture the importance of “Safety”
  - Criteria of initial construction costs and life cycle costs may be better evaluated in a quantitative manner using specific cost information rather than in subjective / qualitative terms (weakly inferior, etc.)
  - Not all of the factors in the excel tool apply to all projects. Adding a feature to turn on and off the factors in the Excel based decision tool can be helpful.

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