University Transportation Research Center - Region 2

Final Report

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

Performing Organization: Syracuse University

August 2017

Sponsor:
University Transportation Research Center - Region 2

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

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16. Abstract

Highway networks in the United States have been suffering from poor operational and structural condition states for the past decades. The consequent congestion problems often result in major delays, safety issues, and large amounts of additional fuel consumption and greenhouse gas emissions. With limited funding available, transportation agencies are placing more emphasis on maintenance, repair, and reconstruction (MRR) practices in order to preserve and restore roadway conditions. Innovative MRR techniques have proved effective or shown great potential in addressing problems associated with poor condition levels of aging asphalt roadway infrastructure with reduced economic, social, and environmental impacts.

In this project, the research team investigated various innovative MRR techniques (e.g. warm mix asphalt, full depth reclamation, cold in-place recycling, and intelligent compaction) and developed decision support tools to assist transportation agencies in identifying the most appropriate MRR techniques in consideration of several technical, economic, social, and environmental factors. More specifically, a survey of state departments of transportation (DOTs) has been conducted, and the results have been utilized in developing decision support tools featuring a decision flowchart and multi-criteria decision making (MCDM) modeling tools using Fuzzy analytical hierarchy process (FAHP) and analytical network process (ANP). The decision support tools have been validated through feedback from NYSDOT officials and case studies based on actual asphalt roadway MRR projects in the State of New York.

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List of Acronyms

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
ASCE	American Society of Civil Engineers
BST	Bituminous Surface Treatment
CIR	Cold In-Place Recycling
DOT	Department of Transportation
FAHP	Fuzzy Analytical Hierarchy Process
FDR	Full Depth Reclamation
FHWA	Federal Highway Administration
GPS	Global Positioning System
HIPR	Hot In-Place Recycling
HMA	Hot Mix Asphalt
IC	Intelligent Compaction
IRI	International Roughness Index
ISO	International Organization of Standardization
ISS	Innovative Soil Stabilization
LCA	Life-cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCCA	Life-cycle Cost Analysis
MCDM	Multi-Criteria Decision Making
MDOT	Michigan Department of Transportation
MRR	Maintenance, Repair, and Reconstruction
NCHRP	National Cooperative Highway Research Program
NYSDOT	New York State Department of Transportation
RAP	Reclaimed Asphalt Pavement
PASER	Pavement Surface Evaluation and Rating
PCI	Pavement Condition Index
PDR	Partial Depth Reclamation
PERT	Program Evaluation and Review Technique
PMS	Pavement Management System
PQI	Pavement Quality Indicator
SMA	Stone Matrix Asphalt
TAMP	Transportation Asset Management Plan
TRB	Transportation Research Board
UBBS	Ultra-thin Bonded Bituminous Surface
VOC	Volatile Organic Compound
WMA	Warm Mix Asphalt

EXECUTIVE SUMMARY

Highway systems in the United States have been suffering from poor functional and structural condition states for the past decades. The condition of the roadways in New York State is reported to be worse than the national average with 60% of roads being in poor or mediocre conditions. The consequent congestion problems often result in major delays and safety issues, along with large amounts of fuel consumption and greenhouse gas emissions. With limited funding available, management of congested highways has become more challenging due to higher rates of deterioration and higher user costs. Therefore, transportation agencies and local governments are placing more emphasis on innovative maintenance, repair, and reconstruction (MRR) techniques that have the potential to reduce the economic, social, and environmental impacts associated with traditional techniques.

This research aims to assist transportation agencies in making informed and holistic decisions in management of existing asphalt roadways by:

1. Investigating innovative MRR techniques for asphalt pavements that can improve the condition of roadways in consideration of economic, social, and environmental impacts,
2. Identifying important factors that affect the decision making procedures in selecting the most appropriate maintenance, repair, and reconstruction technique for asphalt roadways,
3. Developing decision support tools that will allow evaluation of MRR alternatives.

A survey was conducted among State Departments of Transportation (DOTs) to determine the current state of practice in both traditional and innovative MRR methods. The proposed decision support framework consists of a flowchart model for identification of applicable MRR techniques, along with Fuzzy Analytical Hierarchy Process (FAHP) and Analytical Network Process (ANP) based decision-making models to evaluate traditional and innovative MRR techniques. These tools altogether provide a systematic procedure in standardizing the decision making process. The models have been reviewed by NYSDOT officials and validated using case studies in the State of New York.

1 INTRODUCTION

For the past two decades, users of the asphalt roadway systems in the United States have been experiencing various problems due to the poor condition levels of these systems. The Infrastructure Report Cards have evaluated the overall condition grade of roads to be in the range of “D-” to “D+” since 1998 (ASCE 2017). The latest report card showed that 20% of the nation’s highway and 32% of urban roads were in poor condition as of 2014, costing U.S. motorists $112 billion in extra vehicle repairs and operating costs (ASCE 2017). As more frequent maintenance, repair, and reconstruction (MRR) activities are expected to take place in the near future to restore distressed roadways, the selection of proper MRR techniques to be used will have increasingly significant implications.

Federal Highway Administration (FHWA), American Association of State Transportation Officials (AASHTO), and Transportation Research Board (TRB) have emphasized the importance of acceleration of highway and bridge construction projects. FHWA defines accelerated construction as “a strategic process that uses various innovative techniques, strategies, and technologies to minimize actual construction time, while enhancing quality and safety on today’s large, complex and multiphase projects” (FHWA 2014). In addition, with the increasing levels of attention placed on the environmental and social impacts of surface transportation, public agencies are seeking more holistic approaches in determining appropriate courses of action instead of making cost-driven decisions.

Although significant progress has been achieved in accelerated construction of bridges using prefabricated elements and systems along with other innovative techniques and equipment, the maintenance, repair, and reconstruction activities for roadways are still mostly undertaken by traditional methods, resulting in high agency and user costs. In fact, innovative MRR techniques have demonstrated great potential and effectiveness in improving the overall condition of roadways with cost savings as well as lower social and environmental impacts. Some of them, such as warm mix asphalt and cold in-place recycling, have been performed by transportation agencies for many years, while the rest are gaining increasing levels of attention.

Considering that asphalt roadways constitute a large portion of road infrastructure in the United States, it is necessary to (1) identify currently employed maintenance, repair, and reconstruction techniques (both traditional and innovative), and to (2) investigate opportunities to improve asphalt pavement management practices by focusing on MRR techniques that have lower overall impacts. Although various MRR techniques are being used across the nation, the maturity of pavement management systems among State Departments of Transportation (DOTs) differ greatly, and it is challenging for some State DOTs to justify the decision making procedures with regards to selection of innovative techniques. Therefore, there is a dire need for decision support tools that would practically assist in identification of appropriate MRR techniques and evaluation of most beneficial alternatives.

1.1 Objectives and Methodology

The goal of this study is to explore the opportunity of preserving the condition of asphalt pavements while decreasing the overall impacts of related MRR activities. Major objectives of the study include:

1. Investigate traditional and innovative maintenance, repair, and reconstruction techniques for asphalt roadways considering their economic, social, and environmental impacts;
2. Identify and analyze the important factors that affect public agencies' decision making process in selecting the most appropriate maintenance, repair, and reconstruction techniques;
3. Develop a high-level, practice-ready decision support tool that would help public agencies evaluate maintenance, repair, and reconstruction alternatives and justify their final decisions.

In order to fulfill these objectives, a nationwide survey is conducted on innovative asphalt roadway MRR techniques employed by public agencies to identify the current state of practice. Then, important factors that affect the decision making process for selecting appropriate MRR techniques are examined. Based on these findings, high-level decision support tools utilizing a decision flowchart and a multi-criteria decision support (MCDM) model using Fuzzy Analytical Hierarchy Process (FAHP) and Analytical Network Process

(ANP) are developed to assist public agencies in their decision-making process. The research tasks completed include:

1. A comprehensive review of the available literature to understand:
    a. The state of practice in traditional techniques including, but not limited to:
        i. Sealing techniques (chip seal, crack seal, scrub seal, slurry seal, etc.),
        ii. Overlays (thin cold mix overlay, thin hot mix overlay).
    b. The state of practice in innovative techniques including, but not limited to:
        i. Warm mix asphalt,
        ii. Asphalt pavement recycling (partial and full depth reclamation, cold in-place recycling, etc.),
        iii. Other innovative techniques that improve asphalt roadway condition (intelligent compaction, soil stabilization, etc).
    c. Existing decision support models that assist in selecting appropriate alternatives.
2. Survey of public agencies to examine the current state of practice with regards to:
    a. Work completed using traditional and innovative techniques, respectively,
    b. Characteristics and general performance of innovative techniques,
    c. Factors that affect decision making process including, but not limited to:
        i. Initial construction cost and life-cycle cost,
        ii. User cost, Traffic flow, Safety,
        iii. Sustainability-related measures (e.g. CO_2 emissions).
3. Development of customizable decision support tools that allow case-specific selections of appropriate MRR alternatives by determining the significance of each factor and evaluating various MRR strategies.
    a. Decision flowcharts
    b. Multi-criteria decision making methods such as Fuzzy Analytical Hierarchy Process and Analytical Network process
4. Validation of the decision support tools through formal interviews with public agency personnel and application to real-life projects in the state of New York.
5. Finalizing the model and generating a final report to reflect and disseminate research outcomes.

2 BACKGROUND INFORMATION

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.

To thoroughly investigate different techniques used in the management of asphalt roadways, a comprehensive review has been conducted on the traditional and innovative MRR techniques, as well as pavement management systems, both on network level and project level. General information regarding the Multi-Criteria Decision Making (MCDM) methods used in this study, including Fuzzy Analytical Hierarchy Process (FAHP) and Analytical Network Process (ANP), is also provided.

2.1 Traditional MRR Techniques

2.1.1 Sealing Techniques

2.1.1.1 Chip Seal

The earliest mix design procedure for chip seals was developed originally by F. M. Hanson (1934/35) in New Zealand. The fundamentals of this mix design methodology are incorporated in all of the major chip seal mix design methods that are currently being used worldwide (Adams 2014). Chip seal is one of the low-cost alternatives to preserve an asphalt pavement. Terms such as chip seal and bituminous surface treatment (BST) are commonly used in the United States to describe this process; however, terms seal coat and sprayed seal are also used in international practice.

Chip seal mainly consists of two components: asphalt binder, and aggregates (chips). Even though chip seal was initially introduced ninety years ago, the methodology of mixing and applying chip seal has not changed significantly.

The mixture of aggregates and asphalt binder is placed on existing asphaltic pavements as part of a preventative maintenance or pavement preservation program. Chip seals provide a relatively inexpensive permanent surface, protecting the pavement structure and driving surface, as well as the subgrade (Testa and Hossain 2014). Chip seal treatments are designed to improve the condition of the surface layer while mitigating the deterioration of the overall pavement structure. Originally, chip seals were used exclusively for the construction of low traffic volume roads, but with advances in emulsion quality, construction techniques, and overall knowledge, chip seals have evolved into a maintenance alternative that can be successfully used for both low and high traffic volume pavements (Adams 2014).

One of the main benefits of using chip seal is that transportation agencies can choose from a large variety of chip seal types in order to satisfy design considerations. Table 1 summarizes most commonly used BST treatment types and the types of applications in which they are usually practiced.

Table 1 Types of Chip Seal

Type	Description
Single chip seal	A single chip seal involves applying a single layer of aggregates after applying bituminous binder, i.e. asphalt emulsion. Single chip seal is widely used for flexible pavements where no other situations that require a special kind of seal exist.
Double chip seal	A double chip seal consists of two layers of bituminous binder and aggregate application, where aggregates of the top layer are "about half the nominal size" of the bottom layer. A double chip seal is stronger than a single chip seal and is typically used in roads with high-traffic volume.
Racked-in seal	A racked-in seal is a special kind of chip seal typically applied in areas of high turning movements. A layer of choke stone is applied after a single chip seal to prevent loss of aggregates. Choke stones are about half the size of the aggregates used in the first application. This seal allows bituminous binder to cure fully by interlocking the aggregates.
Cape seal	Cape seal was invented in South Africa, and is named after Cape Town. It is a combination of a single seal and a slurry seal. Cape seal provides a "stable matrix" as the second application (i.e., slurry seal) helps to dislodge the larger aggregate particles. Advantages that cape seals provide include smooth and dense surface, good skid resistance, and a relatively long service life.
Inverted seal	Inverted seal is a kind of double chip seal where smaller particles are applied for the first seal without any application of bituminous binder. When pavement shows bleeding, inverted seal is applied to correct this problem.
Sandwich seal	Although two layers of aggregates are applied in sandwich seals, only a single spray of asphalt binder is used in between them. These seals are used to correct "surface texture on raveled surfaces."
Geotextile-reinforced seal	Conventional chip seals are not suitable for cracked road surfaces, which require high-cost rehabilitation or reconstruction. Geotextile-reinforced seals can be applied in these cases. A geotextile fabric is placed on a pavement surface with a light application of asphalt binder, followed by the application of a single seal. Geotextile-reinforced seals are effective in preventing reflective cracking.

Source: Testa and Hossein (2014)

2.1.1.2 Slurry Seal

Slurry seal is another very commonly employed sealing technique, which can be used in treating deteriorated pavement surfaces and extending their lifespan. Slurry seals have been used as a preventative and corrective maintenance technique for pavement surfaces since the late 1920s. Slurry seal consists of a mixture of asphalt emulsion, fine aggregate, mineral filler, and water, as described in Table 2.

Table 2 Components of Slurry Seal

Component	**Description**	**% by Weight**
Emulsified Asphalt	Emulsified asphalt consists of three basic ingredients: asphalt cement, water, and an emulsifying agent.	5 ~ 20
Aggregates	Aggregates used in slurry seal mixes are generally 4.75 mm and smaller. Aggregates should be clean and well-graded. The most commonly used aggregates are granite, slag, mine railings, dolomite, limestone, and siliceous materials. Blending two or more aggregates is usually desirable.	75 ~ 90
Mineral Filler	Mineral fillers are used primarily to improve the gradation of the combined aggregate. The mineral filler can prevent coarser aggregate particles from settling to the bottom of the slurry mix. The most widely used mineral fillers are portland cement, fly ash, and limestone dust.	0.5 ~ 3
Water	Most local water sources are suitable for slurry seal. Water coats aggregate particles before emulsion does, thus reducing the frictional resistance of aggregates and allowing emulsion to more easily coat aggregate particles.	4 ~ 12

Source: Wessley (2012)

These materials are mixed proportionally and placed onto existing pavements using a machine designed specifically for slurry seal (Wessley 2012). The main purposes of slurry sealing are to reduce excessive oxidation of an asphalt surface, improve friction, and seal microcracks. Additionally, slurry sealing helps to mitigate pavement raveling (Wang et al. 2012). According to the research conducted by Hajj et al. (2013), surface lifespan can be increased by approximately 25%, if slurry seal is subsequently applied on a surface according to a pre-determined frequency of application.

Slurry seal is a widely used technique in the United States that became popular among DOTs in 1960's. It has been used frequently over 50 years with some significant changes on only the application techniques. The components used in slurry seal applications remained the same.

2.1.1.3 Crack Seal

Crack seal is an inexpensive option for addressing cracks on pavement surfaces; however, this technique does not increase the lifespan of a pavement substantially and is used to temporarily address pavement performance issues. Although "crack sealing" can be used with the term "crack filling" interchangeably, many states distinguish these two terms. Crack sealing is used to address "working" cracks, which can propagate considerably with changes in temperature and traffic loading. On the other hand, crack filling technique is used for "non-working" cracks that undergo little movement and require less effort to complete the operation (Wang et al. 2012). Crack sealing is performed to reduce infiltration of water into the pavement through cracks, which may otherwise lead to faster deterioration of the surface. 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.

2.1.1.4 Benefits of Sealing Techniques

One of the main benefits of using sealing techniques is that these techniques generally provide an acceptable benefit/cost ratio that allows state DOTs to regularly maintain roads at an adequate quality level. Table 3 compares unit costs of the most commonly used sealing techniques with a major repair of road surfaces.

Table 3 Cost of Preventive Maintenance Treatments

Treatment	**Cost per lane-mile**
2-inch overlay	$20,000-$35,000
Slurry seal	$7,000-$10,000
Chip seal	$7,000-$10,000
Crack seal	$700-$1,000

Source: Testa and Hossain (2014)

Sealing techniques can provide design lives ranging from 1 to 7 years on average, which makes them highly cost effective solutions. When applied on an existing flexible pavement, a selected sealing type will provide a surface wearing course, seal the underlying pavement against water intrusion, enhance or restore skid resistance, and enrich the pavement surface to prevent distresses caused by oxidation. The average service lives of sealing techniques are approximately 5.8 years for chip seal (Mahoney et al. 2014), 5 years for slurry seal, and 3 years for crack seal (Wang et al. 2012).

2.1.2 Overlays

Overlays are used as pavement rehabilitation techniques to increase the service life of pavements substantially by replacing the top layers of deteriorated asphalt with a new thin asphalt layer. Roads need to be locally fixed and prepared in order to ensure adequate binding between the new overlay and the existing road. Traditional hot mix asphalt (HMA) overlays, with lift thicknesses from 1.25 to 2.0 inches, have a long history of successful implementation. Under favorable conditions, they can extend the overall pavement life by 8 to 10 years (Wilson et al. 2015). Before applying a new layer of asphalt, the road condition should be evaluated to determine if partial repair is needed. Table 4 summarizes pre-overlay repair techniques that are commonly used in the US.

Table 4 Pre-overlay Repair Methods

Repair Method	Description
Milling	Milling removes asphalt layers either at a partial depth or the full depth of the pavement.
Mill and Relay	Mill and relay is conducted by milling the existing asphalt layer(s) to a partial depth and then sandwiching the broken (loose) asphaltic materials between the remaining (solid) asphalt layer and the overlay.
Cold In-Place Recycling (CIR)	CIR is accomplished by full-depth milling of the existing asphalt layer(s) and using the broken asphaltic materials as a new base under the overlay.
Surface Patching	Surface patching is performed by removing an area of distressed pavement and backfilling the area with new asphaltic materials. Surface patching is typically followed by milling to obtain a smooth surface for asphalt overlay paving.

Source: Li and Wen (2014)

2.1.2.1 Thin Overlay

Thin overlays are similar to traditional overlays but have a reduced depth that varies from approximately 0.5 inch to 1.25 inch. Thin overlays are considered to be more cost effective because they allow more lane-miles to be repaired using the same amount of materials. However, pavement conditions need to be analyzed very carefully before a decision is made in favor of thin overlays.

Pavements that are failing or have failed cannot be successfully treated with a thin overlay alone; they must be repaired so that a stable foundation is provided before the thin overlay is placed. Thin asphalt overlays are extremely useful as a routine maintenance/pavement preservation technique and are often shown to have lower life-cycle costs in comparison to other types of pavement preservation techniques (NCHRP 2014). The cost of applying thin overlays per ton is generally higher than conventional overlay mixes; however, due to the fact that they are applied in thinner layers, they cost less per square yard (Texas A&M Transportation Institute 2015).

Most commonly used thin overlays can be divided into three categories depending on the aggregate sizes and bonding: dense-graded, gap-graded, or open-graded. Details of these applications are provided in Table 5. Hot mix asphalt (HMA) overlays constitute some of the most commonly used types of thin overlays. These applications include the use of ultra-thin mix, thin overlay mix and Permeable friction course Type F. Those types of thin overlays are examples of dense-graded, gap-graded, and open-graded mixes, respectively.

Another example of thin overlays is Ultra-thin bonded bituminous surface (UBBS), also known as Novachip, which is a preventive maintenance or thin surface treatment technique that consists of a thin, gap-graded hot-mix asphalt (HMA) layer applied over a thick polymer-modified emulsion layer. UBBS helps in treating road distresses such as roughness, rutting, transverse cracking, and fatigue cracking (Musty and Hossain 2014).

Table 5 Categories of Thin Overlays

Type	Description	Application
Dense-graded	Dense-graded mixes for thin overlays have a nominal maximum aggregate size of either 9.5 or 4.75 mm. The coarser mixes can be laid as thin as 0.75 inch and the finer mixes as thin as 0.5 inch. During construction, they are easy to hand-work and compact. The resulting surface is very smooth, thus minimizing vehicle vibrations, a significant source of interior vehicle noise.	These applications are ideal for maintenance applications and they can also be used in new construction. For maintenance purposes, they can correct raveling, rejuvenate weathered surfaces, seal against further oxidation, and restore micro-texture on polished sections. The pavement should be free of structural deficiencies such as fatigue cracking or active rutting.
Gap-graded	Gap-graded mixes for thin overlays are referred to as stone matrix asphalt (SMA) and can have a nominal maximum aggregate size of either 9.5 or 4.75 mm, which are laid as thin as 0.75 and possibly 0.5 inch. SMA mixtures are more durable than traditional dense-graded mixes due to high binder content and a strong coarse aggregate skeleton or matrix. The space created within the matrix is filled with asphalt-rich mastic. SMA mixes are, therefore, rut resistant yet still flexible and impermeable. However, these mixes can be difficult to compact.	These applications can correct low to moderate severity cracking and raveling, and low-severity rutting. They can correct polished surface problems but should not be applied to flushed pavements. Pavements should be free of structural deficiencies e.g. fatigue cracking or active rutting problems. Minor rutting (< 0.25 inch) may be allowable; but larger irregularities should be corrected with a leveling course or milling first.
Open-graded	Open-graded mixes for thin overlays use a uniformly graded aggregate mix with a nominal maximum aggregate size of 9.5 mm (material passes the 3/8 inch sieve but is retained on the No. 4 sieve). They also use a small portion of fibers to prevent the binder from draining down. The result is a stone-on-stone contact mix with an open structure, leading to good nighttime visibility, very good surface drainage, greatly reduced splash-and-spray and risks of hydroplaning.	This type of overlay works well in maintenance applications. It can correct low-severity cracking, low-severity rutting, and restore skid resistance. It is a particularly good option for flushed pavements, since the open aggregate skeleton allows expansion of the excessive binder.

Source: Wilson et al. (2015)

2.1.3 Total Reconstruction

In total road reconstruction, all of the layers of an old pavement are removed and new layers are put in place. Total reconstruction is an ultimate solution to increase road quality, if none of the rehabilitation and maintenance techniques are effective. Due to a significant increase in the number of roads showing severe deficiencies in the last decades, transportation authorities are shifting their focus mainly onto rehabilitation and maintenance of existing roads, as total reconstruction of all of these roads would be too costly. Before constructing a new road or completely reconstructing an old one, it is important to evaluate all the options for new layers of the road that will be placed. Roads, in general, consist of the following layers from bottom to the top: subgrade, subbase, base and asphalt layers.

2.1.3.1 Subgrade

The subgrade is the natural ground, graded and compacted, on which the pavement is built. In order to prepare a subgrade it is necessary to address the following steps presented by American Concrete Pavement Association (1995): First, the soils need to be compacted to ensure uniform and stable pavement support. Second, whenever possible, gradelines need to be set sufficiently high and side ditches should be made sufficiently deep in order to increase the distance between the water table and pavement. Third, crosshauling and mixing of soils should be done to achieve uniform conditions in areas where there are abrupt horizontal changes in soil type. Then, selective grading in cut and fill areas can be used to place the soil exhibiting better characteristics near the top of the final subgrade elevation. Finally, extremely poor soil should be improved by treating with cement or lime, or by importing soil from other sources.

2.1.3.2 Base and Subbase

Subbase and base layers are generally the thickest layers of a pavement section. These layers serve as a support for the surface layer and distribute the wheel load to subgrade material. They also help to slow down the intrusion of fines from the subgrade soil into pavement structural layers, minimize the damage of frost action, prevent accumulation of free water within or below the pavement structure, and provide a working platform for construction equipment.

Base and subbase layers generally consist of a combination of sand, gravel, crushed stone, and recycled material. They are classified in accordance with their gradation and the amount of fines. The gradation of aggregates can affect structural capacity, drainage, and frost susceptibility. The quality of aggregate base and subbase material affects the rate of load distribution and drainage (Caltrans 2008).

Base and subbase layers can be divided into two major categories: treated base/subbase and treated permeable base/subbase. The treated type of bases and subbases can also be divided into hot mix asphalt base and others, as shown in Table 6.

Table 6 Treated and treated permeable types of Bases/Subbases

<table>
<tr><th colspan="2">Base/Subbase Type</th><th>Description</th></tr>
<tr><td rowspan="2">Treated Base and Subbase</td><td>Hot Mix Asphalt Base</td><td>Depending on the quality of aggregates, Hot Mix Asphalt Base is classified as dense graded Type A or Type B HMA. Type A is primarily a crushed aggregate layer, which provides greater stability than Type B. When used with HMA pavement, the Hot Mix Asphalt Base is to be considered as part of the pavement layer.</td></tr>
<tr><td>Other treated bases and subbases</td><td>Materials mixed with asphalt, Portland cement, or other stabilizing agents to improve the strength or stiffness of granular material. These materials include lean concrete base, cement treated base, asphalt treated base, and lime treated subbase.</td></tr>
<tr><td colspan="2">Treated Permeable Base and Subbase</td><td>These layers provide a strong, highly permeable drainage layer within the pavement structure. The binder material may be either asphalt or Portland cement. Either of these Treated Permeable Base layers will generally provide greater drainage capacity than is needed. The standard thickness is based primarily on constructability with an added allowance to compensate for construction tolerances. In certain applications, it may be necessary to check the permeability and adequacy of the layer thickness.</td></tr>
</table>

Source: Caltrans (2008)

2.1.3.3 Asphalt

Asphalt is the most commonly used material for the top layer of roads due to many reasons: Asphalt pavement structures can be designed to handle any load, from passenger cars to heavy trucks. Asphalt produces smooth, durable, safe, and quiet pavements. Surface mixes can be customized to absorb noise, to reduce splash and spray during rainstorms, and even to help treat rain water (National Asphalt Pavement Association 2017).

Hot mix asphalt (HMA) is the most commonly used type of pavement layer and it usually consists of asphalt binder, mineral aggregate, air, and modifiers in some cases. Modifiers such as polymers, elastomers and fibers are binder modifiers; while lime, granulated rubber, and anti-strip agents are considered to be aggregate modifiers. Modern HMA production involves using different size distribution (gradation) aggregate stockpiles, which are introduced into the plant through a set of feed bins or directly fed from the stockpiles. These aggregates are mixed and dried in a drum dryer, and mixed with asphalt to be stored in insulated silos for use in pavement construction (Awuah-Offe and Askari-Nasab 2011).

Hot mix asphalt is classified into three categories: dense-graded (sizes of aggregates are evenly distributed from the smallest to the largest); open-Graded (mostly consisting of coarse aggregates with few fines); and Stone Matrix Asphalt (SMA) (mid-size aggregates are missing or reduced in quantity).

2.2 Innovative Maintenance, Repair, and Reconstruction Techniques

2.2.1 Warm Mix Asphalt

Warm mix asphalt (WMA) refers to asphalt concrete mixtures that are produced at lower temperatures (by 50°F or more) than the temperatures typically used in the production of hot mix asphalt (HMA). First introduced in Europe in the late 1990s, WMA was designed to reduce greenhouse gas emissions while providing mixtures with similar strength, durability, and performance characteristics as traditional HMA (Bonaquist 2011). The first WMA pavement in the United States was constructed in 2004, followed by hundreds of field trials (West et al. 2014).

There are generally three categories of WMA technologies: asphalt foaming technologies, organic additives, and chemical additives. Asphalt foaming technologies usually rely on the use of water-injecting system, damp aggregate, or the addition of a hydrophilic material to foam asphalt by turning water to steam, dispersing throughout the asphalt, and expanding the binder to temporarily increase its volume and fluids content (West et al. 2014). The main processes of additive technologies, both organic and chemical, are summarized in Table 7.

Table 7 Warm Mix Asphalt Additive Technologies

Technology	**Description**	**Details**
Organic Additives	Generally wax, such as Fischer Tropsch or Montan waxes	a. In the US, Sasobit wax (Fischer-Tropsch wax) is mainly used. b. Melting point is 100°C (212°F) and completely soluble in asphalt above 140°C (284°F). c. Sasobit has a different crystalline structure and longer carbon chain.
Chemical Additives	Surfactants or other chemical additives	a. Relatively new for WMA. b. Help binders coat the aggregate at lower temperatures. c. Reduce internal friction between the binder and aggregates during mixing and compaction.
Water-bearing Additives	Synthetic zeolites	a. Composed of aluminosilicates and alkalimetals. b. Contains crystalline water which is released as the temperature is increased over 100°C (212°F). c. Water creates a foaming effect that increases volume of the binder and decreases viscosity. d. Slow release of water from zeolite provides for an extended period of workability.
Water-based processes	Non-additive processes based on foaming	a. WAM Foam: two-stage process where soft asphalt binder first coats the aggregate followed by a hard asphalt binder that is foamed. b. Low energy asphalt – uses heated coarse aggregate blended with asphalt binder and wet fine aggregate to complete foaming. c. Double Barrel Green process – mixing chamber where water is injected through nozzles and the asphalt binder is foamed (single stage foaming). Most prevalent process in the US.

Source: Anderson et al. (2008)

In comparison to HMA, the use of WMA techniques offers several major advantages:

Late Season (Cool Weather) Paving: case studies in Europe show that WMA could be properly performed at ambient temperatures of as low as -3°C (about 27°F) (D'Angelo et al. 2008). Although actual WMA production temperatures vary based on haul distance, ambient temperature, and other factors, they are expected to be lower than HMA production temperatures under the same conditions. Since WMA mixture can be produced at lower temperatures and remain compactable for a longer period of time than HMA, pavement contractors have the opportunity to continue paving activities later into the year.

Better Workability and Compaction: It is reported that the roller train for WMA is often tighter together than that for HMA, which means the rolling process is less likely to create gaps in mat coverage, resulting in fewer roller passes and an overall faster process to achieve the target density. Therefore, pavement contractors are expected to deliver more consistent compaction using WMA techniques (Anderson et al. 2008).

Increased Reclaimed Asphalt Pavement (RAP) Usage: Currently the amount of RAP allowed to be used in traditional HMA pavement construction is restricted by some State Departments of Transportation because of the fact that high amount of RAP contributes to the aging of the asphalt mixture, resulting in a higher potential for early cracking and reduced durability. However, since WMA is produced at a substantially lower temperature, the asphalt binder would not be as aged as in HMA, making it possible to have an increased amount of RAP without causing early cracking. Case studies in Europe indicate successful use of RAP at up to 50%, while in the United States, the amount of RAP in most of the WMA projects is usually at or below 20% (D'Angelo et al. 2008).

Reduced Fuel Use: The fuel use reduction in WMA is largely achieved by reductions in the use of burner to dry and heat aggregates. Every drop of 10°F in the asphalt mixture exit temperature generally corresponds to a 2 to 3 percent of decrease in fuel consumption, and fuel savings of WMA are reported to be in the range of 10% ~ 35% (Prowell and Hurley 2007; Young 2007). The actual fuel consumption reduction is affected by many factors including type of fuel used, stoichiometric volume of air ratio used in plant operation, dryer exhaust temperature, entrance temperature and percent moisture to be evaporated from aggregates, as well as plant elevation (Anderson et al. 2008).

Reduced Plant Emissions: A major source of emissions during asphalt production stage is the dryer, which generates combustion emissions (NO_x, SO_2, CO_2, CO, and VOCs) and non-combustion emissions (water, particulate matter, VOCs, polycyclic aromatic hydrocarbons, aldehydes, organic residues, and hazardous organics) in the form of gases or particulate matters (Mejias-Santiago and Osborn 2014). Table 8 shows the range of reduction for major types of emissions observed in WMA practices in Europe.

Table 8 Emission Reductions by using WMA

Emission	Reduction of Emission by % Through WMA
CO2	15 – 40
SO2	18 – 35
NOx	18 – 70
VOC	19 – 50
CO	10 – 30
PM	25 – 55

Source: D’Angelo et al. (2008); Anderson et al. (2008)

Improved Working Conditions for Paving Crews: Similar to reductions in emissions of greenhouse gases and pollutants, a decrease in emissions of asphalt aerosols, fumes, and polycyclic aromatic hydrocarbons is also observed during WMA placement. As an example, German Bitumen Forum indicates a reduction of 30 – 35% in such emissions (D’Angelo et al. 2008). Therefore, paving crews are expected to experience less exposure to organic matters, which reduces the risk of exposure to potential health hazards. In addition, reduction of visible smoke and odor during WMA placement may also contribute to improved working conditions (Anderson et al. 2008).

In order to be considered as a more favorable alternative to traditional HMA, it is vital that WMA can provide comparable performance along with the many benefits discussed above. Performance characteristics of WMA is summarized in Table 9 according to the research findings of the NCHRP project 09-43 (2011), in which mix design and analysis procedures were developed for various WMA processes based on laboratory testing and field validation from case studies in different states. Following the recommendations of AASHTO R30, R35, T283, and T312, the WMA processes are expected to provide mixtures with similar or superior properties compared to HMA processes (Bonaquist 2011).

Table 9 Performance Characteristics of WMA versus HMA

Properties	**Performance Characteristics**
Volumetric Properties	• Volumetric properties of properly designed WMA and HMA mixtures are very similar. • For HMA mixtures with 1.0% binder absorption or less, properties of a WMA design are essentially the same as those of an HMA design.
Binder Grade Selection	• Same grade of binder should be used in WMA and HMA mixtures designed for the same project location. • Decrease in the recovered binder stiffness is only significant at extremely low production temperatures.
RAP in WMA	• New binders and RAP mix at WMA process temperature if sufficient length of time is allowed • Planned field compaction temperature for WMA should exceed the high-temperature grade of the "as recovered" RAP binder.
Short-Term Oven Conditioning	• Short-term oven conditioning of two hours, same as that for HMA mixtures
Coating, Workability, and Compactability	• Degree of coating depends on type of mixer used. • Workability of WMA differs from that of HMA at compaction temperature ranges. • Compactability is sensitive to the compaction temperature, the WMA process, and the presence of RAP in the mixture.
Moisture Sensitivity	• WMA including anti-strip additives improves the tensile strength ratio of some mixtures.
Rutting Resistance	• Same level with HMA by two hours of conditioning and then less than 16 hours of extended loose mix conditioning at a representative high in-service pavement temperature

Source: Bonaquist (2011)

2.2.2 Asphalt Recycling

There has been a growing trend of conserving materials and energy during the last two decades, due to the scarcity of high quality materials and higher levels of awareness with regards to the importance of sustainability. In road construction, specifically, with limitations on funding, state transportation agencies are taking measures to replace the traditional methods of milling and overlay or total reconstruction with more cost-effective and sustainable practices (Jensen et. al 2008). Furthermore, repetitive asphalt overlays to existing pavements result in raised road levels and cause corrosion and drainage problems. Hence, recycling of the old pavement materials started to become economically and technically preferable (Reddy et al. 2014).

The use of reclaimed asphalt pavement (RAP) dates back to 1915. It gained popularity in 1970s when the price of asphalt binder increased dramatically. However, it was not until recently that guidelines for mix design of asphalt mixtures using RAP were developed, as an NCHRP project in 2013 investigated best practices of RAP (Willis and West 2014). Based on a survey conducted by FHWA (Hansen and Copeland 2014) the industry witnessed a substantial growth in use of RAP in the United States from 12% in 2008 to 20% in 2013. A major concern with asphalt pavement recycling is the uncertainty regarding long-term service life, as the increased oxidation in RAP is expected to result in excessive stiffness and elevated cracking. The lack of documentation and data for long-term performance of recycled pavements furthered such concerns.

In-place pavement recycling has the capability of restoring the structural capacity of distressed pavements with minimized need for virgin materials. This is usually accomplished by hot in-place recycling (HIPR), cold in-place recycling (CIR), or full-depth reclamation (FDR).

2.2.2.1 Hot In-Place Recycling

Hot in-place recycling (HIPR) has been internationally recognized as an effective MRR method to rehabilitate asphalt pavements with distresses such as raveling, cracks, ruts, and holes while making minimum use of virgin materials. HIPR typically consists of reclaimed asphalt mixture, virgin asphalt, new aggregates, and rejuvenator additives that on average account for 3% of the overall content and allow softening of aged asphalt (Zou et al. 2015). It is critical to perform recycling at an appropriate temperature: low temperature results in insufficient softening of asphalt pavement surface, while high temperature changes the performance characteristics of recycled asphalt. In order to treat various levels of distresses, variations of HIPR methods are used. These variations include surface recycling, repaving, and remixing for surface irregularities and cracks, deficiencies in the upper 25-50 mm, and pavement problems to a depth of 40-50 mm, respectively.

A case study in Florida reported that the cost of constructing a highway pavement section with HIPR was 40% of the cost of constructing it using conventional techniques from a life-cycle perspective, because of the environmental benefits achieved through decreased amount of virgin aggregates used, decreased emissions from transportation of materials, and shortened construction duration (Ali and Grzybowski, 2012).

2.2.2.2 Cold In-Place Recycling

Similar to HIPR, the Cold in-place recycling (CIR) technique is very effective in addressing asphalt pavement deficiencies such as cracking, rutting, bumping and shoveling (Gao et al. 2014). CIR refers to a rehabilitation process in which the existing pavement materials are reused in-place without the application of heat. Specific steps of performing CIR include milling 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 mix. Foamed asphalt is a product obtained through the following process: asphalt cement is heated and pumped through an expansion chamber on the cold recycling unit, a small amount of cold water is injected and vaporized, which causes the asphalt cement to rapidly foam (Lane and Lee 2014).

A shorter construction period, reduction in transportation and production of virgin materials, and reduction in fuel consumptions and greenhouse gas emissions are among the most widely recognized benefits of using CIR. Due to the absence of heating, RAP 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. In a Roads and Bridges / Asphalt Recycling & Reclaiming Association Recycling Award winning road rehabilitation project in California, the use of CIR technique with two layers of overlay on top of the recycled pavement resulted in a six week early finish and $785,000 cost savings with minor traffic delays (Zagoudis 2015). Another project in Ontario Canada, 2003, integrated typical CIR and foamed asphalt technologies, introduced as CIREAM, and delivered asphalt pavements with satisfactory tensile strength both by the end of construction period and after ten years of service (Lane and Lee 2014).

2.2.2.3 Full Depth Reclamation

Full depth reclamation (FDR) is a 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 the recycling agents used in CIR (such as active fillers, asphalt emulsion, and foamed asphalt), which aim at restoring 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 may otherwise contribute to the formation of reflective cracks and other forms of distresses. When 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.

It should be noted that as FDR is a relatively new process, there is a lack of a unified mix design procedure, and each pavement section is being rehabilitated differently based on its specific conditions. This condition can be viewed as a challenge in the utilization of this technique (Swiertz 2015).

In a four-lane highway section rehabilitation project in Boquete, Panama where humidity and precipitation was extremely high, FDR was used to address pavement deficiencies caused by the lack of proper drainage. A depth of 125 mm was reclaimed with an average RAP content of 80%, and the tensile strength test results showed that the recycled pavement met the AASHTO specifications (Fabrega et al. 2015).

2.2.3 Intelligent Compaction

Compaction is one of the most critical processes in asphalt pavement construction and largely determines the long-term performance of paved roadways and whether the expected service life can be achieved (Horan et al. 2012). The effectiveness of rehabilitation using asphalt overlays is also heavily affected by the quality of compaction. Therefore, stiffness and density tests are usually conducted following compaction as a quality control process. The limitation of this procedure is that these tests mostly use point measurements to collect stiffness and density data, and the measurements only account for a small portion of the total compacted area. There is a risk of not being able to identify regions that have not been properly compacted through conventional stiffness and density tests.

In order to ensure sufficient coverage of the compacted area, intelligent compaction (IC) technique can be utilized, where compaction process is monitored and controlled by instrumentation. Intelligent compaction achieves more uniformed compaction and 100% coverage of the compacted area by: (1) continuous assessment of mechanistic soil properties through roller vibration monitoring, (2) automatic feedback control of vibration amplitude and frequency, and (3) integration of global positioning system (GPS) for a complete geographic information system-based record of earthwork site (Savan et al. 2015). These efforts are completed with the system components described in Table 10.

Intelligent compaction was introduced in the United States in 2004 following its successful implementation in Europe, but its adoption has experienced a slow growth (Mooney et al. 2010; Nieves 2014). So far IC specifications have been drafted or adopted by over ten state departments of transportation (Savan et al. 2015).

Table 10 Configurations of Intelligent Compaction Systems

Component	**Position**	**Purpose**
GPS	Mounted over the cab of a roller	Accurately locate the roller on the project
Accelerometer	Mounted on the roller frame near the vibratory drum	Measure the vertical acceleration of the roller frame as the roller moves.
Infrared Temperature Sensor	Mounted on the front and rear of the roller	Monitor the mix surface temperature and create a temperature log
Processing Software	In the cab of the roller	Conduct real-time analysis to provide a continuous profile of the level of compaction by combining vertical acceleration data with other various data
Visual Display	In the cab of the roller	Show real-time compaction information, including roller amplitude, frequency, GPS location, and seed, in both numerical and graphical settings
Data Storage	In the cab of the roller	Complete digital record for monitoring and documentation purposes.

Source: Mooney et al. (2010)

IC has been reported to improve compaction efficiency and create cost savings from a life-cycle perspective. Firstly, IC allows paving contractors to closely monitor the stiffness of the materials being compacted in order to minimize variability in the end product. This results in fewer passes of rollers to achieve the desired level of compaction, thus optimizes labor utilization, shortens construction time, reduces fuel consumption, and minimizes equipment wear-and-tear. A case study shows that IC instrumentation helped create 37% cost savings and 23% schedule reduction, while the additional costs of IC rollers accounted for a marginal percent of the overall cost (Savan et al. 2015). Secondly and perhaps more importantly, IC offers identification of areas that have not been properly compacted so that reworking of defective areas can be planned before additional layers are placed. As a result, improved quality control and assurance can be achieved and maintenance requirements can be reduced. Lastly, contractors using IC can have access to construction records for future references. A major concern associated with IC is the lack of an industry-wide standardized measure to report compaction results of IC rollers. Major manufacturers of IC rollers including Amman/Case, Bomag, Caterpillar, Dynapac, HAMM, and Sakai generally use different measures (Nieves 2014).

Table 11 summarizes the benefits of innovative techniques in this study.

Table 11 Summary of Benefits of Innovative MRR Techniques

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

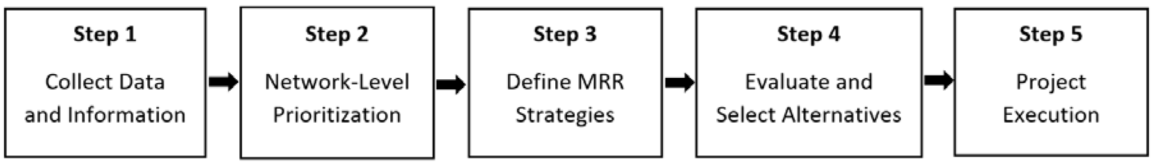
2.3 Existing Decision Making Tools for MRR of Asphalt Roadways

Due to the funding constraints and large number of roadways with deficiencies, optimization of expenditures and development of procedures to select the most appropriate MRR strategies are gaining tremendous importance. Meanwhile, in order to effectively manage MRR activities for any type of civil infrastructure, one would rely on access to accurate and up-to-date information. A decision support tool, or sometimes a decision support system, refers to the use of computers to store, analyze, and display such information that is then used to support decision making (Uddin et al. 2013). As integral components of infrastructure asset management systems, decision making tools replace the past practices that heavily depended on personal experience and judgment, which can be biased and less cost-effective.

For asphalt roadways, decisions on MRR activities are typically made through a pavement management system (PMS), which provides network-level condition scores for each pavement section and recommends remedial actions ranging from routine maintenance to major rehabilitation or reconstruction based on a set of criteria reflecting agency's interests (Rada et al. 2012). American Association of State Highway and Transportation Officials (AASHTO) in 1993 defined pavement management as "a set of tools or methods that assist decision-makers in finding optimum strategies for providing, evaluating, and maintaining pavement in a serviceable condition over a period of time", and provided Pavement Management Guide in 2001 and 2012 (AASHTO 2001; 2012).

A typical pavement management system starts from data collection and integration. Condition assessment and modeling are then performed on a network level for prioritization purposes, followed by development of MRR alternatives and treatment selection, which is usually undertaken by local or regional agencies. Figure 1 is a simplified display of essential steps in a pavement management system.

Figure 1 Simplified Components in a Pavement Management System



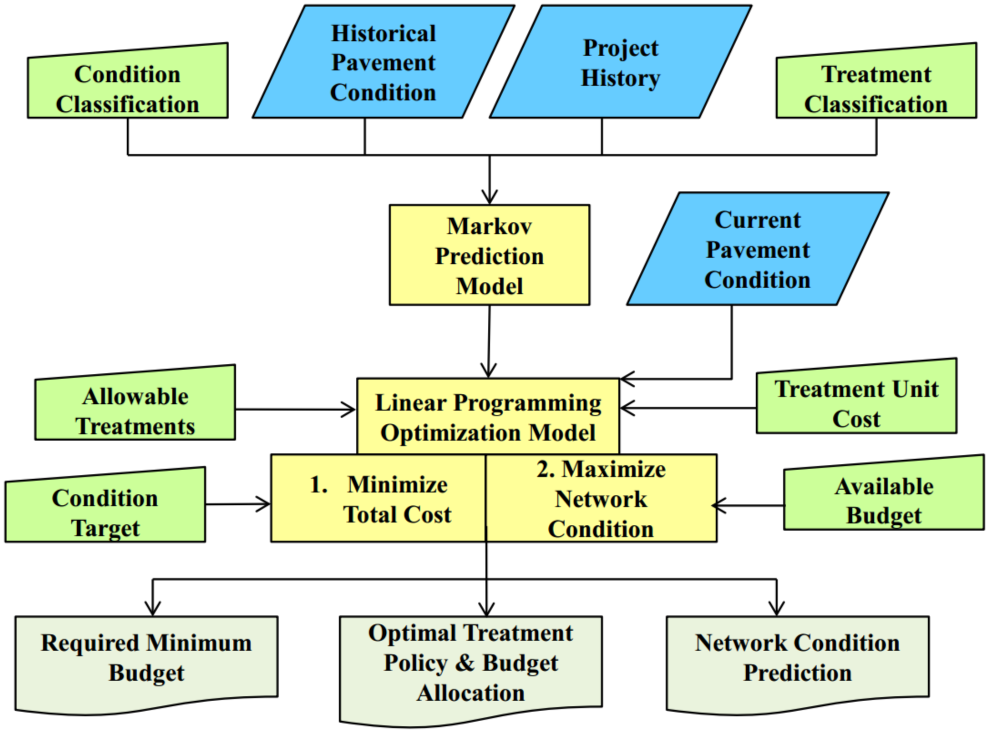
Source: Rada et al. (2012); AASHTO (2012)

2.3.1 Network-Level Pavement Management System

Since the release of the ISO 55000 Standards for Asset Management in 2014, transportation agencies with varying maturity levels in infrastructure management have been taking measures to adhere to the guidelines of the Standards or make further improvements on their current asset management practices. Since pavements account for a major component of public infrastructure, the adoption of high-level pavement management systems or other equivalent decision support systems is becoming a necessity among state departments of transportations. Figure 2 shows a network-level optimization flowchart used by Ohio Department of Transportation as an example of a high level asset management decision support tool (Chou and Williams 2012).

Data collected, analyzed, and stored in a pavement management system typically include inventory data (route number and type, functional class, length, pavement type, number of lanes and width, etc.), pavement condition (measure by IRI, PCI, PQI, PASER, or other parameters), traffic and loads, costs (construction, preventive and routine maintenance, rehabilitation, and reconstruction), as well as history (Vitillo 2009)

Figure 2 Network Level Optimization Flowchart

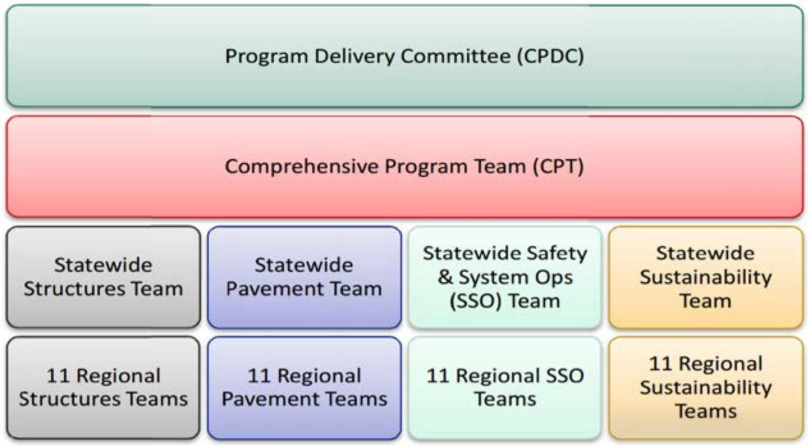


Source: Chou and Williams (2012)

The department managerial structure under which data are processed and transferred is equally important. Figure 3 depicts the asset management business structure of New York State Department of Transportation (NYSDOT) including statewide and regional teams (McDonald 2014). Again, the decision making on prioritization takes place at the state level, while that on MRR alternative evaluation and strategy selection generally falls within the jurisdiction of regional management teams.

The data models and management architectures are sometimes integrated in commercial off-the-shelf pavement management software which are utilized by some state DOTs to manage their civil infrastructure. Schattler et al. (2011) discussed eight pavement management software developed by public and private domains that are used widely throughout the United States and are of particular interest to local agencies in Illinois. A summary of pavement software features is shown in Figure 4.

Figure 3 NYSDOT Asset Management Business Structure



Source: McDonald (2014).

Figure 4 Comparison of Pavement Management Software Features

CRITERION DESCRIPTION	PAVEMENT MANAGEMENT SOFTWARE PROGRAMS							
	PUBLIC				PRIVATE			
	MicroPAVER	**RoadSoft GIS**	**Utah LTAP TAMS**	**StreetSaver**	**RoadCare**	**PAVEMENTview Plus**	**PubWorks**	**PavePro Manager**
Vendor	U.S. Army Corps of Engineers	Michigan Technological University - Center for Technology & Training	Utah Local Technical Assistance Program	Metropolitan Transportation Commission	Applied Research Associates	Cartegraph	Tracker Software Corporation	Infrastructure Management Services
Website	www.apwa.net	www.roadsoft.org	www.utahltap.org	www.mtcpms.org	www.ara.com	www.cartegraph.com	www.pubworks.com	www.ims-rst.com
Laptop Data Collection	Yes	Yes	Yes	Additional program needed	*	Yes	Yes	*
Ability to Analyze Other Assets	No	Yes, signs, pavement markings, traffic counts, & traffic crashes	Yes	Yes, sidewalks, lights, sign, curb and gutter, & user-defined	*	Yes, sewer, signal, sign, storm, bridge, & lights	Yes, bridges, signs, culverts, guardrails, parks, & buildings	*
Default Pavement Condition Rating Measure	PCI	PASER	RSL	PCI	PCI, IRI	OCI	PASER	*
Analyzes Different Maintenance Strategies	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Analyzes Different Budget Scenarios	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
GASB 34 Reporting	No	Yes	No	Yes	*	Yes	Yes	*
GIS Integration	Yes	Yes	Additional Software needed	Additional Software needed	Additional Software needed	Additional Module-GIS director or own software	Addition module MapViewer needed	Additional software needed
Customization Capabilities	Yes	Only certain aspects	Yes	Yes	*	*	Additional modules available	Additional modules available
Cost (2011)	APWA members $995; non-members $1095	Contact vendor for more information	Utah-free/Out of state $500	$1500+, contact vendor for more information	Varies, contact vendor	Varies, contact vendor	Varies, contact vendor	Varies, contact vendor
User's Manual	Yes	Yes	Yes	Yes	*	Yes	Yes	*
Technical Assistance	Training courses or four-part web-based training	Telephone or web-based training	Free Telephone or paid on-site arrangements	4-day training class twice per year and customized on-site training	*	On-site or web-based training; technical support by phone	Formal training at 1 day per module, free updates, software helpdesk	*

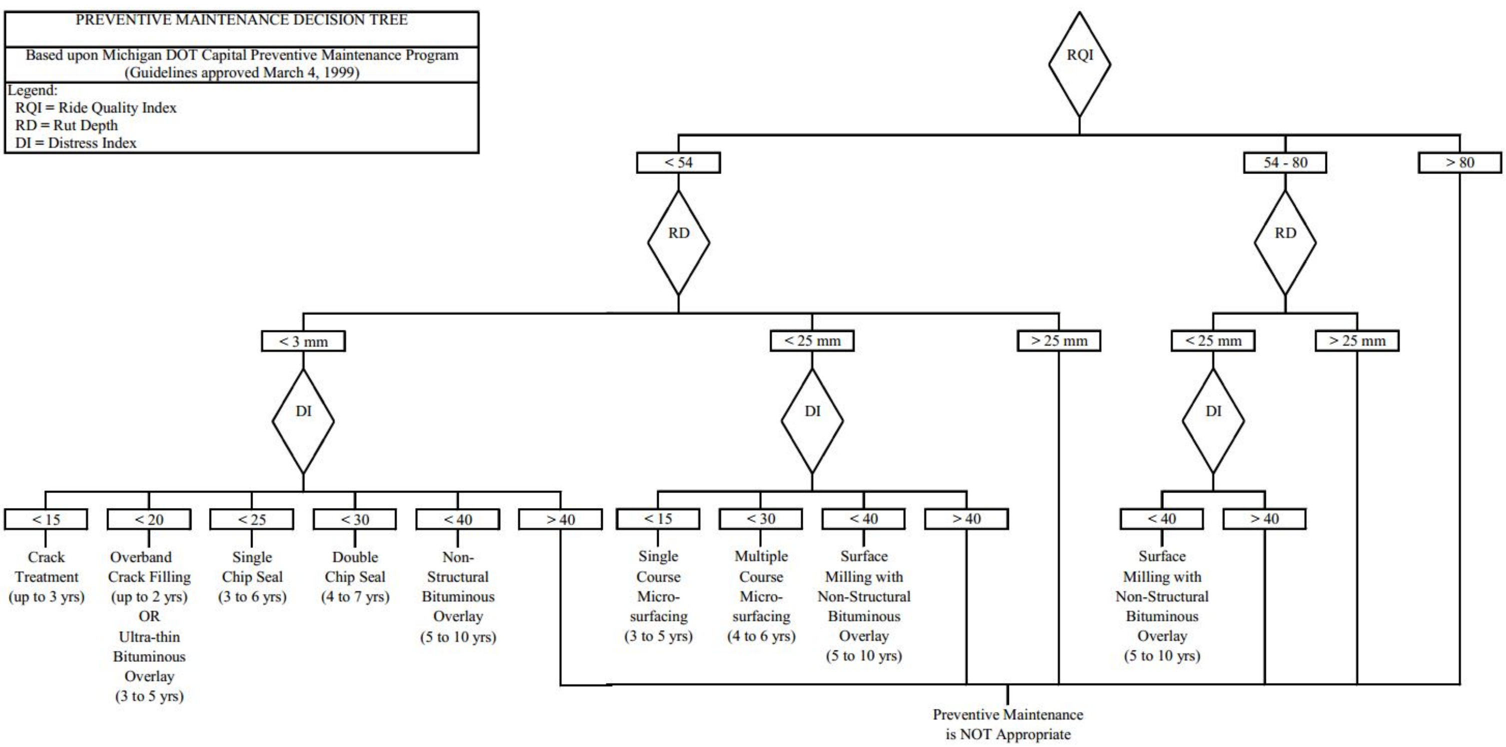
[1] PCI – Pavement Condition Index; PASER – Pavement Surface Evaluation and Rating System; RSL – Remaining Service Life; IRI – International Roughness Index; OCI – Overall Condition Index
(*) Denotes: Unable to obtain information at this time. Contact vendor for more information.

Source: Schattler et al. (2011)

2.3.2 MRR Alternative Selection

Once the network-level prioritization is completed and the roadway segments to be repaired or rehabilitated are determined, the project-level duties (such as planning and executing appropriate MRR activities) are typically transferred to regional offices. A pool of MRR alternatives is generally developed based on the capabilities of different asphalt pavement maintenance and rehabilitation methods in addressing existing deficiencies. Selection amongst MRR alternatives is generally accomplished through the use of decision trees and decision matrices, both of which depend on rules and criteria determined by the agency. Hicks et al. (2000) conducted a comprehensive discussion on features of such decision trees and matrices, and provided various examples of the tools that state DOTs used for flexible pavements. Figures 5 and 6 show the decision tree and matrix used by MDOT and NYSDOT, respectively.

Figure 5 MDOT Decision Tree on Preventive Maintenance



Source: Hicks et al. 2000

Figure 6 NYSDOT Alternative Preventive Maintenance Treatments

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.

Source: Hicks et al. 2000

The advantages of using a decision tree or matrix to identify potential MRR alternatives include: (a) the ease of use and presentation, (b) consistency with agency experience, and (c) the flexibility of customizing decision criteria. However, a decision tree or matrix usually incorporates a limited number of important factors for treatment selection, features no or little comparison of multiple alternatives, and allows limited use of new and innovative treatment methods. With these disadvantages, decision trees or matrices are only suitable for addressing project-level decision-making problems that exhibit low variation, but not suitable for network-level evaluation and optimization (Hicks et al. 2000).

Similar to the development of MRR alternatives, the selection of the best strategy is also mostly agency-specific. However, the principles are generally the same, and considerations when making decisions include but are not limited to (Hall et al. 2001):

- Geometric restrictions
- Experience of agency and contractor
- Availability of materials and equipment

- Construction duration
- Worker safety during construction
- Traffic impacts and safety during construction
- Environmental impacts

Life Cycle Cost Analysis (LCCA) is a very commonly used method among transportation agencies in selecting the optimum MRR alternatives. In the LCCA approach, all significant costs of construction or MRR activities, both from agencies' and roadway users' perspectives, are taken into consideration. Federal Highway Administration (2004) developed the software program titled "RealCost" for transportation agencies to quantify the differential costs and to analyze investment alternatives for an optimized outcome for a given project.

It should be noted that LCCA may result in overlooking of factors that are difficult to be monetized. Because of the fact that many innovative MRR techniques excel in reducing environmental impacts and improving sustainability of transportation agency's performance, the use of LCCA to evaluate innovative MRR techniques may result in biased or sub-optimal outcomes. Therefore, a more comprehensive method is needed for this purpose.

2.3.3 Life Cycle Assessment

Life cycle assessment (LCA) is a methodology to evaluate the environmental impacts of a product over its entire life cycle, starting from material extraction to the end-of-life disposition (Santero et al. 2010). The environmental impacts typically analyzed by LCA include resource use, air and soil pollution, impact on surface water, noise, direct impacts on nature and landscape, electromagnetic radiation or fields, and ionizing radiation.

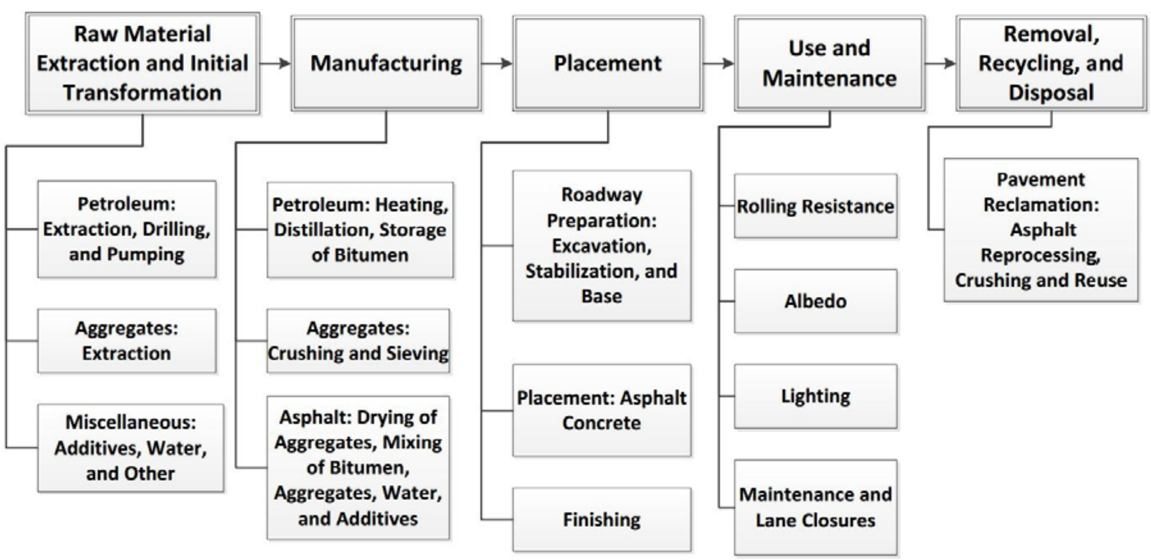
LCA framework provided by International Organization of Standardization (ISO) (2006) consists of four stages including goal definition, life cycle inventory, life cycle impact assessment, and life cycle interpretation, as summarized in Table 12. Specifically, phases and components included in LCA of flexible pavements are shown in Figure 7 (Loijos 2011).

Table 12 LCA Stages and Steps

Stage	Step
Goal Definition	• Define project goals • Determine type of information needed and level of specificity • Determine data organization and result display • Define scope of the study • Determine ground rules for performing the work
Life Cycle Inventory (LCI)	• Develop diagrams to map inputs and outputs • Develop data collection plans • Collect data using LCA software • Evaluate and report results
Life Cycle Impacts Assessment (LCIA)	• Select and define relevant environmental impact categories • Organize and combine LCI results into defined categories • Characterize impacts using conversion factors • Present commonly used LCI categories with examples • Normalize impact indicator results by category comparison • Assign weights to categories based on respective importance • Evaluate and document LCIA results and verify their accuracy
Life Cycle Interpretation	• Identify significant issues • Evaluate completeness, sensitivity, and consistency of data, • Draw conclusions and provide recommendations

Source: ISO (2006)

Figure 7 Life Cycle Phases and Components for Asphalt Pavements



Source: Loijos (2011)

As discussed in the research goals and methodology, the overarching objective of this study is a high-level decision support framework for selection of MRR techniques considering multiple factors from economic, social, and environmental perspectives. The wide variations in types of distresses, and construction and location specific characteristics that can be observed in existing asphalt roadways directly affect the feasibility of potential MRR alternatives. Conducting an LCA for such a large pool of possibilities (pairs of existing pavement state and potential solutions) requires highly time consuming and resource intensive data collection and analysis efforts. Furthermore, the assumptions and decision made in such an analysis will restrict the transferability and applicability of results to large populations of roadway segments. Therefore, in this study the research team used qualitative factors in capturing environmental impacts of various MRR alternatives and incorporated these factors to the decision making tools rather than using an LCA-based approach.

In summary, existing decision support tools that state departments of transportation currently utilize are either working in a "black box" manner with little room for customization (e.g. commercial software), focusing heavily or even solely on economic factors (e.g. LCCA tools), or lacking the coverage of innovative MRR techniques as alternative strategies (e.g. decision matrices). Therefore, a decision support framework that (1) comprehensively covers both traditional and innovative MRR alternatives, (2) allows customizable, quantitative evaluation of alternatives based on factors from economic, social, and environmental perspectives, and (3) still features ease of use and consistency with the current practices of transportation agencies is needed.

2.3.4 Multi-criteria Decision Making Methods

The research team investigated several multi-criteria decision making processes with regards to their capabilities in adequately addressing the importance of non-economic factors when making decisions with regards to selection of MRR techniques.

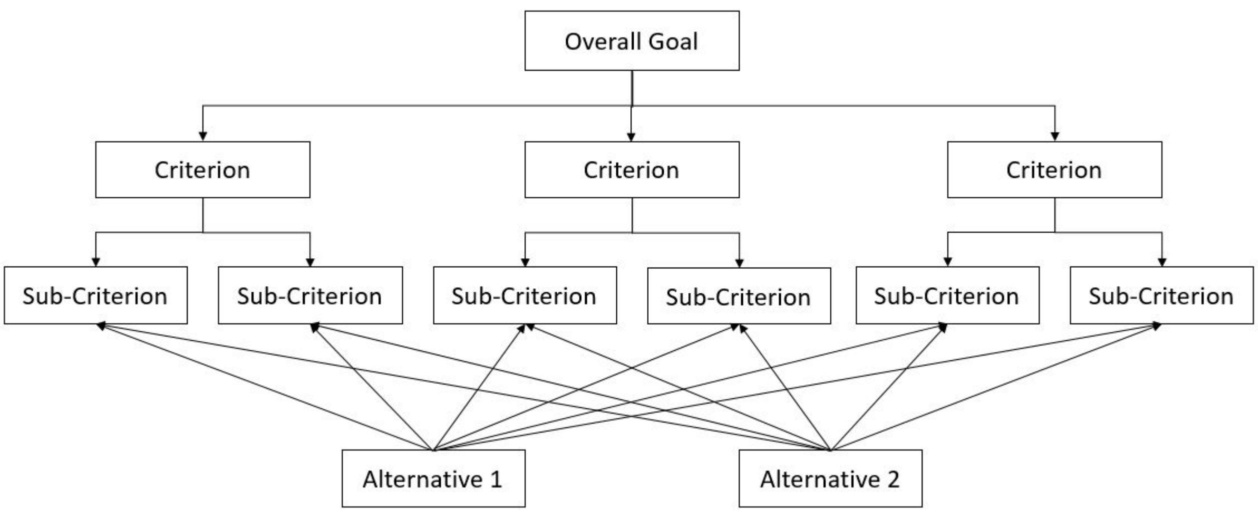
2.3.4.1 Analytical Hierarchy Process

Analytical hierarchy process (AHP) is a widely adopted pairwise comparison model for multi-criteria decision making, which was developed by Saaty in 1970. AHP incorporates logic, intuition, experience, judgment, and personal values in the analysis and considers all factors while reaching the final conclusion (Saaty 1982).

AHP starts with defining hierarchies (see Figure 8) 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 usually 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 of the higher level followed by the weighing process on the lower level.

Benefits of using AHP include the ability to model a wide range of unstructured problems with ease of understanding, the similarities of the technique to the natural tendencies of human rational thinking process, the capability of incorporating intangible factors, and flexibility in customization by adjusting the relative priorities to match the changing goal.

Figure 8 Schematic Representation of Decision Hierarchy for AHP



Source: Adapted from Saaty (1982).

To set up an AHP model for decision making, one should take the following steps:

- Define the problem and goal;
- Build the hierarchical structure with criteria and sub-criteria;
- Develop pairwise comparison matrix describing the impact of each element in the criterion hierarchy. In the matrix, elements on the left are examined regarding their respective dominance over the elements at the top. Due to

symmetry, only one part (above or below the diagonal line) of the matrix is populated. Therefore, the matrix consists of numbers indicating relative importance, along with their reciprocals in diagonally opposite places. Numbers representing the relative importance of one element over another usually follow the scale of 1 to 9, shown in Table 13. Expert judgment and opinions should be obtained regarding the importance or impact level of the element under investigation;

- Complete the matrix for all levels and categories in the hierarchy;
- Assign weights to the priority vectors representing the weights of the criteria and sub-criteria; and
- Evaluate the consistency of the whole hierarchy by calculating the consistency index and consistency ratio. In order to ensure effectiveness of the decision support tool, the consistency ratio should be less than or equal to 0.1. The quality of the information, the structure of the problem, or the way that questions are developed can be improved, if the consistency ratio exceeds 0.1.

Table 13 Ratio Scale for AHP Pairwise Comparison

Importance	**Definition**	**Explanation**
1	Equal importance of both elements	Two elements contribute equally to the property
3	Weak importance of one element over another	Experience and judgment slightly favor one element over another
5	Essential or strong importance of one element over another	Experience and judgment slightly favor one element over another
7	Demonstrated importance of one element over another	An element is strongly favored and its dominance is demonstrated in practice
9	Absolute importance of one element over another	The evidence favoring one element over another is of highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgments.	Compromise is needed between two judgments
Reciprocals	If activity *i* has one of the preceding numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

Source: Saaty (1982)

2.3.4.2 Fuzzy Analytical Hierarchy Process

Fuzzy analytical hierarchy process (FAHP) integrates the method of fuzzy logic and Saaty's AHP decision making model in order to improve the ability of addressing issues of ambiguity. Fuzzy logic, developed by Dr. Zadeh in 1965, is widely used with the purpose of representing approximate information due to different modes of reasoning that are approximate. Fuzzy logic can address issues of ambiguity by modeling linguistic variables such as "most" and "usually" (Yager and Zadeh, 1992), FAHP is expected to have improved capability of modeling complex problems where it is difficult to describe the relative importance between elements with crisp values.

Fuzzy logic consists of four major elements, including:

1. Linguistic variables qualitatively and quantitatively described with fuzzy sets,
2. Fuzzy sets with non-crisp, overlapping boundaries,
3. Possible distributions that form a membership function to dictate the value of a linguistic variable in a fuzzy set, and
4. Fuzzy if-then rules to define a functional mapping or a logic formula.

The application of fuzzy sets to the AHP is done through replacing the crisp values that describe the relative importance in pairwise comparison matrices with fuzzy numbers with fuzzy membership functions. Triangular membership functions are among the most commonly used functions in this process.

A triangular fuzzy number can be represented by a triplet (*l*, *m*, *u*), and its membership function, $\mu_M(x)$, can be defined as (van Laarhoven and Pedrycz 1983):

$$\mu_M(x) = \begin{cases} \frac{1}{m-l}x - \frac{l}{m-l}, x \in [l, m], \\ \frac{1}{m-u}x - \frac{u}{m-u}, x \in [m, u], \\ 0, \quad otherwise \end{cases} \tag{1}$$

Operation laws for two triangular fuzzy numbers M_1 (l_1, m_1, u_1) and M_2 (l_2, m_2, u_2) are (Chang 1996):

$$M_1 + M_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{2}$$

$$M_1 \times M_2 = (l_1\, l_2, m_1\, m_2, u_1\, u_2) \tag{3}$$

$$M_1 / M_2 = (l_1/u_2, m_1/m_2, u_1/l_2) \quad (4)$$

Two types of FAHP relative importance ratio scales in the form of triangular membership functions are defined in Table 14. The final outcomes for a FAHP are also in the form of triangular fuzzy numbers which can be transformed into membership functions. This way, decision makers will be able to not only identify the most suitable alternative (the highest scoring or the furthest to the right at the figure of membership functions) but also see the degree of ambiguity in the conclusion.

Table 14 Ratio Scales of FAHP

Definition	Type I	Type II
Equal importance of both elements	(1, 1, 1)	(1, 1, 1)
Weak importance of one element over another	(2/3, 1, 3/2)	(2, 3, 4)
Essential or strong importance of one element over another	(3/2, 2, 5/2)	(4, 5, 6)
Demonstrated or very strong importance of one element over another	(5/2, 3, 7/2)	(6, 7, 8)
Absolute importance of one element over another	(7/2, 4, 9/2)	(9, 9, 9)

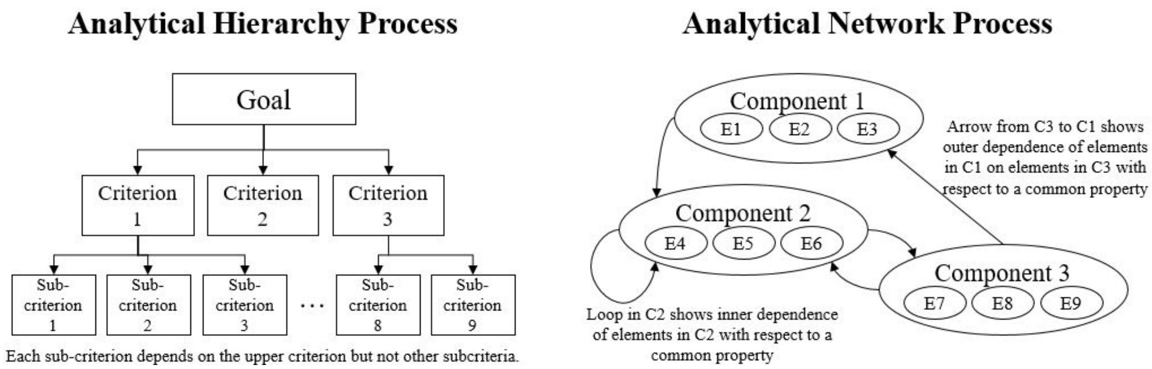
Sources: van Laarhoven and Pedrycz (1983); Chang (1996); Alias et al. (2009); Ayhan (2013).

2.3.4.3 Analytical Network Process

Analytical network process (ANP) provides a general framework in the form of a network to deal 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 in a hierarchy. The difference in system composition of AHP and ANP is shown in Figure 9 (Saaty 2004).

In ANP, one needs to make judgments regarding the relative importance of two elements and also regarding their relative influences on a third element with respect to a criterion. In this manner, with more intensive calculation requirements, ANP is capable of analyzing the dependency between and among alternatives and criteria, and it is reported to provide more accurate modeling results under complex decision making conditions. Because of the capability in modeling interdependencies of elements, especially the feedback effect from low-level factors to high-level factors, ANP method is adopted in decision environments where influences of criteria and alternatives on each other cannot be overlooked (Saaty 2004).

Figure 9 Hierarchy and Network



Source: Adapted from Saaty (2004)

General steps in modeling MCDM problems using ANP include (Saaty 2004):

- Develop structure of decision model;
- Conduct pairwise comparisons on clusters and nodes;
- Form the supermatrix that includes relative weights of sub-matrices from pairwise comparison results;
- Normalize supermatrix to obtain stochastic columns; and
- Raise the supermatrix to limiting powers until the weights have converged.

3 SURVEY OF STATE DOTs

3.1 General Information

In order to identify the current practices with regards to both traditional and innovative maintenance, repair, and reconstruction (MRR) methods and to explore the opportunity of promoting the adoption of innovative asphalt pavement MRR techniques across the nation, a survey of ten questions was distributed to state Departments of Transportation (DOT) that agreed to participate in the study.

A total of 34 agencies responded to the survey. Table 15 summarizes the survey questions, and the full questionnaire survey form is provided in Appendix 1. It should be noted that for some of the questions number of valid responses was less than 34. Nevertheless, the survey provided the research team with an extensive amount of experience and insight with regards to the use of innovative MRR techniques.

Table 15 Summary of Survey Questions

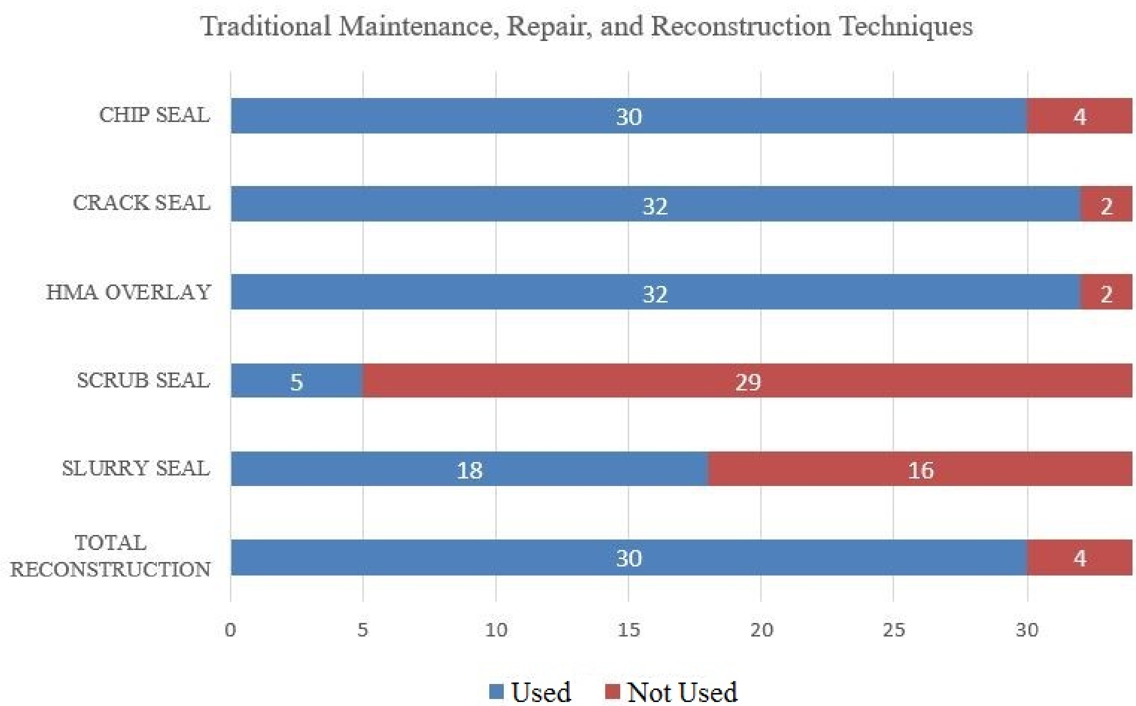
Question	Description
1	Traditional MRR techniques used in the last five years
2	Amount of work competed using traditional techniques in the last five years
3	Innovative MRR techniques used in the last five years
4	Planned pilot projects innovative techniques
5a	If agency neither used innovative techniques nor is planning to, what are the potential reasons?
5b	If innovative techniques are used, what is the amount of work, cost, estimated service life, and construction time for each technique?
6	General performance of projects using innovative techniques in terms of schedule, cost, quality, and safety.
7	Rank factors based on respective importance for decision making process.
8	Amount of Reclaimed Asphalt Pavement (RAP) used in related projects
9	Challenges faced while adopting innovative techniques
10	Decision support systems used in determination of MRR techniques

3.2 Survey Results

3.2.1 Question 1: Adoption of Traditional Techniques

As shown in Figure 10, responses collected from 34 state DOTs indicate that Chip Seal, Crack Seal, and Hot Mix Asphalt (HMA) Overlay were the most frequently performed traditional MRR methods. More than 30 states indicated that they used these methods (more specifically, 30, 32, and 32 states, respectively). Slurry Seal was used by 18 states and Scrub Seal was used by only five states. Among the 33 states, Kansas, Missouri, Nevada, and Texas DOT are using all of the traditional methods listed in the survey.

Figure 10 Number of State DOTs that Used Traditional MRR Techniques



Other traditional MRR techniques applicable for asphalt pavements, such as Microsurfacing, Cape Seals, Fog Seal, and Ultra-Thin HMA Overlay, were also reported to be currently used by various states. It is worth noting that microsurfacing, in which a polymer modified binder is used along with high quality aggregates, has been adopted by 12 state DOTs.

3.2.2 Question 2: Practice of Traditional Techniques

Among all traditional MRR techniques, Chip Seal was the most extensively used technique by the state DOTs in United States, followed by Crack Seal and HMA overlay. More specific information regarding the utilization of traditional MRR techniques is shown in Table 16 and summarized as follows:

- More than half of the Chip Seal work in the last five years was completed in Texas. North Carolina and Virginia followed Texas with considerable volumes of Chip Seal work.
- North Carolina Department of Transportation was the leading agency in the use of Crack Seal and HMA Overlay techniques.
- Virginia was the dominant state in terms of the volume of Slurry Seal projects completed.
- Kansas, Tennessee, and Missouri were the only three states, which reported to use the Scrub Seal technique.
- The use of Total Reconstruction is relatively evenly distributed among all 30 states that responded positively for this technique.
- Regarding other traditional pavement MRR methods: Florida reported using Mill and Resurface extensively; Maryland reported using HMA patches, and Virginia reported using Latex Modified Slurry Seals.

Table 16 Work Completed by Traditional MRR Techniques

Traditional Pavement MRR Techniques	Number of State DOTs				Total*	Top 3 DOTs
	<100*	100-1000*	>1000*	N/A		
Chip Seal	10	10	6	4	43179	TX, NC,VA
Crack Seal	4	14	6	6	27139	NC, IN,NY
HMA Overlay	7	12	8	3	24874	NC, VA, PA
Scrub Seal	3	0	0	27	25	KS, TN, MO
Slurry Seal	27	0	0	3	1548	VA, PA, NC
Total Reconstruction	23	1	0	6	787	PA, SC, MO
Other	9	1	3	0	5220	FL, MD, VA

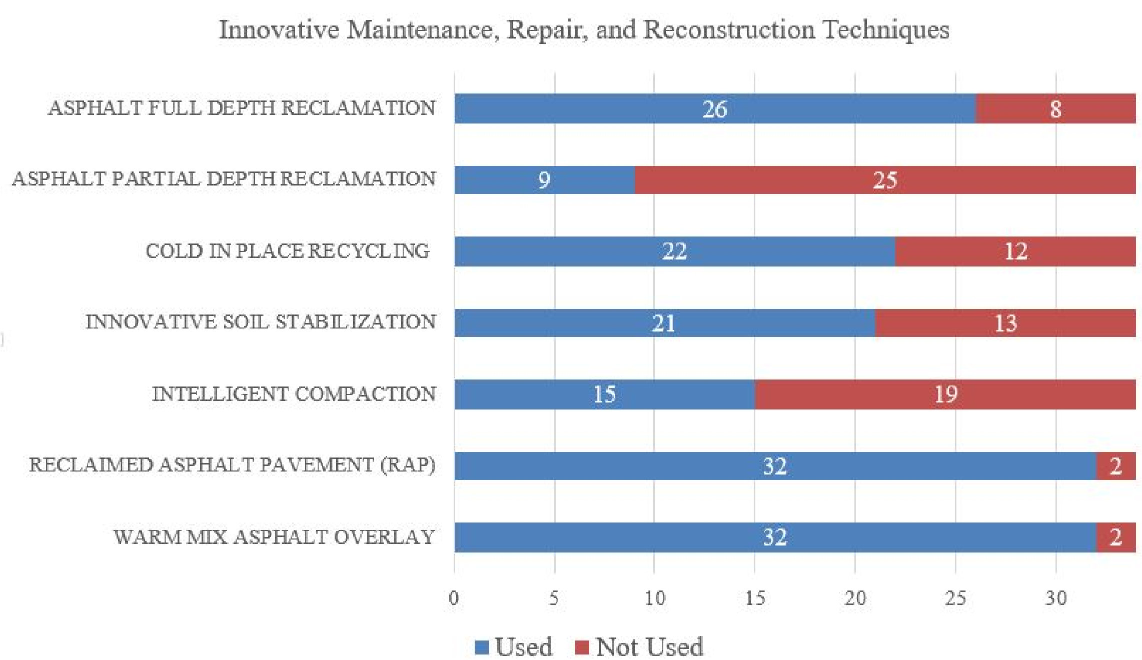
**Amount of work completed in Lane Miles/Year*

3.2.3 Question 3: Adoption of Innovative Techniques

According to the responses collected from 34 states, as shown in Figure 11, innovative MRR techniques, including Warm Mix Asphalt (WMA) Overlay, Asphalt Partial or Full Depth Reclamation, Reclaimed Asphalt Pavement (RAP), Cold In-Place Recycling (CIR), Intelligent Compaction, and Innovative Soil Stabilization, have been broadly utilized to address asphalt pavement deficiencies across the nation.

WMA and RAP were the two most commonly used methods, adopted by 94% of the states surveyed. Asphalt Full Depth Reclamation (FDR), CIR, and Innovative Soil Stabilization also had usage rates above 60%, while less than half the state DOTs surveyed reported utilizing Intelligent Compaction. Partial Depth Reclamation was the least commonly used technique among all innovative MRR techniques.

Figure 11 Number of State DOTs that Used Innovative MRR Techniques



Some other techniques were also reported to be used by state DOTs such as Fiber Mat and Cold Plant Mix Recycling. It is also worth noting that North Dakota and Texas DOTs reported that they have utilized all the innovative MRR techniques listed in the survey.

3.2.4 Question 4: Pilot Projects with Innovative Techniques

23 out of 30 DOTs responded reported that they were planning to undertake pilot projects in the near future featuring Full Depth Reclamation, Cold In-Place Recycling, Hot In-Place Recycling, and Intelligent Compaction.

3.2.5 Question 5a: Reasons for Not Implementing Innovative Techniques

In regards to reasons why projects using innovative techniques have not been executed or planned, South Carolina DOT specified that lack of familiarity and lack of experienced contractors in the region were two major reasons. The latter reason was also shared by Washington State DOT. Florida DOT attributed the absence of innovative techniques to their complete satisfaction with milling and resurfacing technique, which is highly appropriate due to the geotechnical conditions and availability of materials in the region.

3.2.6 Question 5b: Characteristics of Innovative Techniques

Table 17 summarizes some of the key characteristics of innovative MRR techniques, such as average cost, expected service life, and construction time. Among the seven innovative techniques surveyed, Warm Mix Asphalt (WMA) and Reclaimed Asphalt Pavement (RAP) were the most extensively used, followed by Full Depth Reclamation (FDR) and Cold In-Place Recycling (CIR); while Intelligent Compaction (IC) was only tested in pilot projects.

With regards to cost per lane, CIR is reported to be the most expensive technique. It is reported that FDR has the potential to generate the longest expected service life of over 17 years on average, and both RAP and Innovative Soil Stabilization techniques can provide an expected service life of over 15 years. Some agencies also reported that certain innovative MRR techniques, such as WMA and RAP, have construction times equivalent to that of traditional techniques. Construction time for other techniques, including Partial Depth Reclamation (PDR), CIR, Intelligent Compaction, and Innovative Soil Stabilization (ISS), vary greatly from one DOT to another. Agencies also reported additional innovative MRR techniques that were used on a smaller scale, such as Cold Plant Recycling, Fiber-Mat, Diamond Grinding, and bonded concrete overlay.

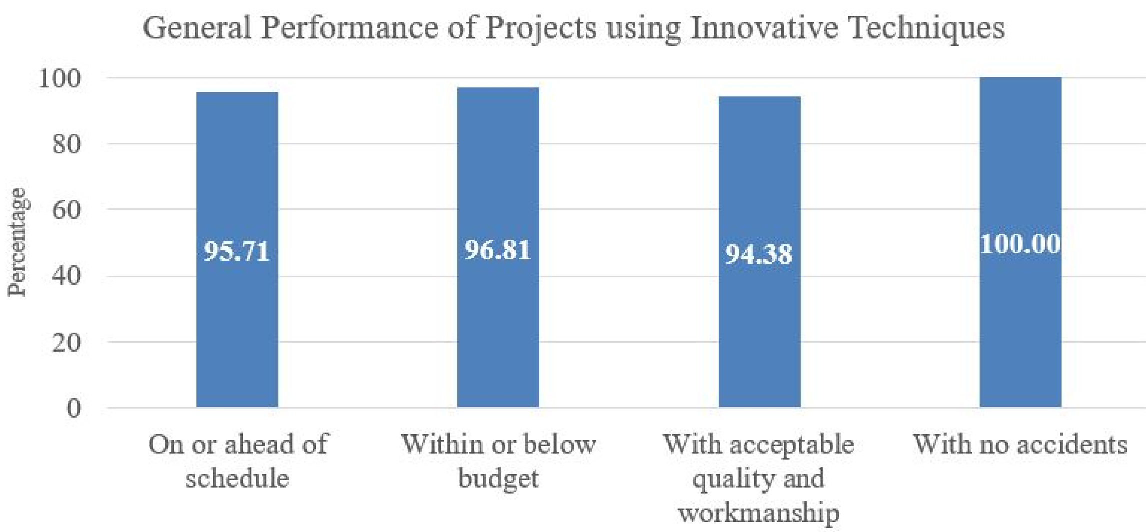
Table 17 Characteristics for Innovative Techniques

Innovative Methods	Number of DOTs	Average lane miles per year	Average Cost per lane mile	Expected Service Life	Construction Time
WMA	22	10 – 600	$205,000	12.5 years	Same as HMA
FDR	19	3 – 200	$478,625	17.4 years	Same as traditional
PDR	3	7 – 50	$7,000	8 years	Varies
RAP	21	100 – 1000	$283,000	12.6 years	Same as traditional
CIR	15	1 – 150	$583,000	15.4 years	Varies
IC	8	Only in Pilot Projects	$105,000	N/A	Varies
ISS	9	5 – 100	N/A	15.5 years	Varies
Other	7	Less than 20	Varies	Varies	Varies

3.2.7 Question 6: Performance in Projects using Innovative Techniques

Disregarding the responses of "unknown", over 90% of the innovative MRR projects were completed on or ahead of schedule, within budget, and with satisfactory quality. It was also reported that all of the projects using innovative techniques were completed without any accidents (see Figure 12).

Figure 12 General Performance of Projects Using Innovative Techniques



3.2.8 Question 7: Factors Affecting Decision Making Process

Agencies were asked to rank a number of factors based on their respective importance for the decision-making process regarding whether innovative MRR techniques should be utilized. On a scale of 1 to 5, ratings were assigned to each factor, with 1 representing the lowest level of importance and 5 representing the highest level of importance. Table 18 provides the average ratings and standard deviation values for ten factors from the original questionnaire and two additional factors specified by respondents under the "other" category.

Table 18 Factors Affecting Decision-Making and Their Average Importance Ratings

Factors Affecting Decision-Making	Average Rating	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

* Factors specified by respondents under the "other" category in the questionnaire.

3.2.9 Question 8: Use of Reclaimed Asphalt Pavement

A large variation was observed among the 32 state DOTs whose use of RAP ranged from 0 to 45%. Only three state DOTs (IA, SC, and WI) reported use of RAP content less than 5%. Generally state DOTs allow a lower percentage of RAP to be used for surface layers than the lower layers, and even lower percentages for high volume roads. More detailed information regarding the maximum RAP content used among the 32 state DOTs is presented in Figure 13 and summarized below:

- Seven states (NV, OH, TN, MT, CO, CT, and AL) use more than 5% RAP, with an upper limit of 15%;
- Six states (SD, TX, UT, MO, HI, and PA) use more than 15% RAP, with an upper limit of 20%;
- Five states (ND, NH, NJ, IN and WV) use more than 20% RAP, with an upper limit of 25%;
- Eleven states (WA, KS, DE, NC, OR, NY, MD, VA, FL, MI, and NE) use between

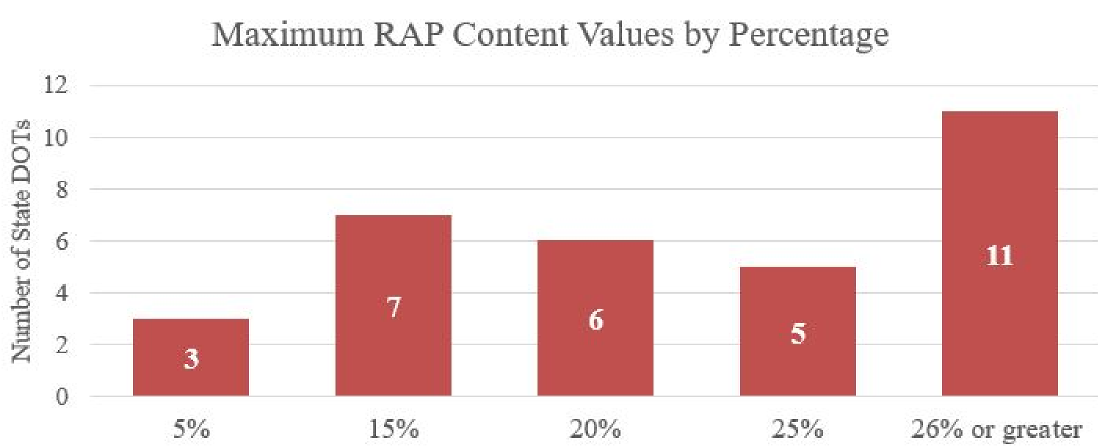
26% and 45% RAP

i. Florida, Michigan, and Nebraska State DOTs reported RAP use of 26%, 29%, and 37%, respectively;

ii. Kansas Department of Transportation typically permits contractors to use up to 25% RAP. RAP content greater than 26% is allowed, if its hardened binder meets the temperature requirement;

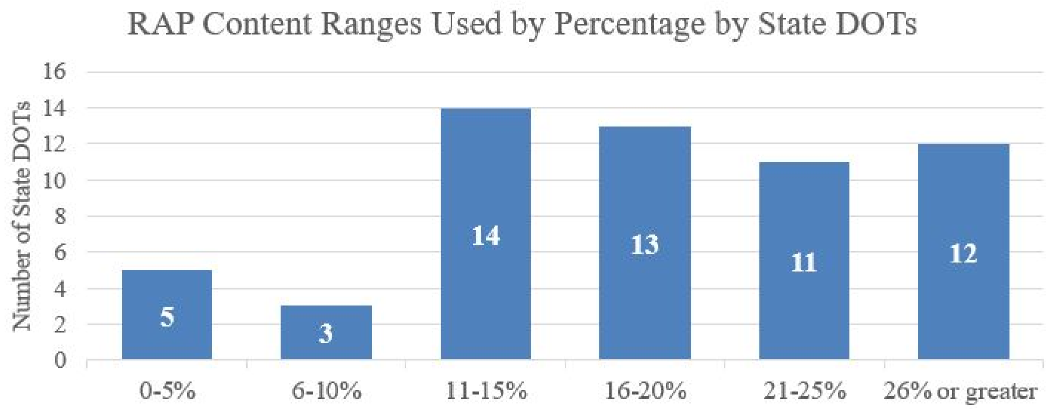
iii. In 2015, North Carolina DOT completed nearly 70% of their RAP related work with 30% RAP use, and only 0.1% of their work with 45% of RAP use.

Figure 13 Maximum RAP Content Values Adopted by State DOTs



The ranges of RAP content used by State DOTs are summarized in Figure 14. It should be noted that the total number of state DOTs exceed 32, as agencies usually use more than one range of RAP content. A rough estimation based on the survey results shows that the average RAP content used by the responding state DOTs falls between 15% and 20%, which is consistent with the value reported by Hansen and Copeland (2014).

Figure 14 RAP Content Ranges used by State DOTs



3.2.10 Question 9: Challenges in Adopting Innovative Techniques

Responses collected for this question are summarized in Table 19. Although technical challenges vary greatly from one technique to the other, some challenges, such as lack of experienced contractors, were common among all the techniques.

Table 19 Challenges in Adopting Innovative Techniques

Common Challenges	Challenges Specific to Certain Techniques	
Limited contractor availability; Lack of design guidelines; Construction difficulties; Insufficient knowledge and in-house training; High initial cost.	WMA	Potential negative impacts on roadway durability
	FDR	Curing may be delayed by unexpected weather
	RAP	Difficulty in tracking certifications of materials; Lack of long-term performance data, May result in brittle failure and early deterioration
	IC	Ineffective data processing and utilization; Unable to guarantee compaction quality in terms of stiffness

3.2.11 Question 10: Use of Decision Support Systems

13 out of 30 states indicated their agency possessed decision support systems. Common sources of information included pavement management systems, commercial off-the-shelf software programs, or research deliverables from universities.

- Seven states (Maryland, Montana, New York, North Dakota, Tennessee, Virginia, and Wisconsin) established pavement management systems or programs to analyze and select most appropriate MRR strategies.
- Ohio, Connecticut, and West Virginia state DOTs use commercial software to

support their decision making process.

- North Dakota DOT Planning Division uses a software program in addition to a pavement management program for decision-making purposes.
- South Carolina Department of Transportation is utilizing a decision support tool developed by Clemson University primarily for management of pavement preservation projects.

It should be noted that some state DOTs may have been using a DSS without explicitly referring to it as a DSS. Therefore, the actual number of state DOTs using a DSS may be larger than the reported number.

3.3 Additional Surveys

In order to gain more insights regarding the application and performance of innovative techniques utilized at the local level in the United States, the research team contacted roadway MRR experts and crews from ten large cities in the United States. The research team also intended to expand the survey efforts by adding Canadian Ministries of Transportation (at the province level in Canada) to the pool of respondents. The same questionnaire survey that was previously sent to state DOTs was sent electronically to shortlisted local agencies in the U.S. and Canadian agencies.

The survey effort focusing on local agencies and Canadian provinces was not as fruitful as the initial survey of state DOTs, with no response collected from U.S. cities and only four responses collected from Canadian provinces. Therefore, the research team decided to document these survey responses instead of analyzing them (please see Appendix II for a detailed summary of responses). The most significant issue encountered during this survey effort was that only few cities have their own city level departments of transportation with specific websites and clear contact information of their employees. For most cities in the U.S., local roads are managed by departments that are named differently throughout the states, making it difficult to find the right contact person. Among the ten cities the research team electronically contacted, only three agencies replied and provided information of personnel who could be of assistance in completing the questionnaire, but unfortunately no response was received after the surveys were distributed.

3.4 Conclusions

Based on the literature review and survey conducted by the research team, several conclusions can be drawn with regards to the use of innovative asphalt roadway maintenance, repair, and reconstruction (MRR) techniques:

- Traditional asphalt roadway MRR techniques such as chip seal, crack seal, and HMA overlay are extensively used by State Departments of Transportation (DOTs).
- For innovative asphalt roadway MRR techniques, use of recycled asphalt pavement and warm mix asphalt have already been widely adopted. A considerable number of DOTs are undertaking pilot projects featuring less commonly used methods such as cold in-place recycling and intelligent compaction.
- While various advantages of innovative MRR methods have been acknowledged and verified, there are still challenges associated with utilization of innovative MRR techniques, including lack of experienced contractors, lack of in-house training, and high initial investment requirements.
- State DOTs have regarded initial construction cost, life cycle cost, and condition of existing roadway among the most important factors while considering utilization of innovative MRR techniques. Meanwhile, user fuel consumption, greenhouse gas emissions, and amount of virgin materials used were among factors with lower levels of importance for state DOTs.

4 DECISION SUPPORT TOOLS

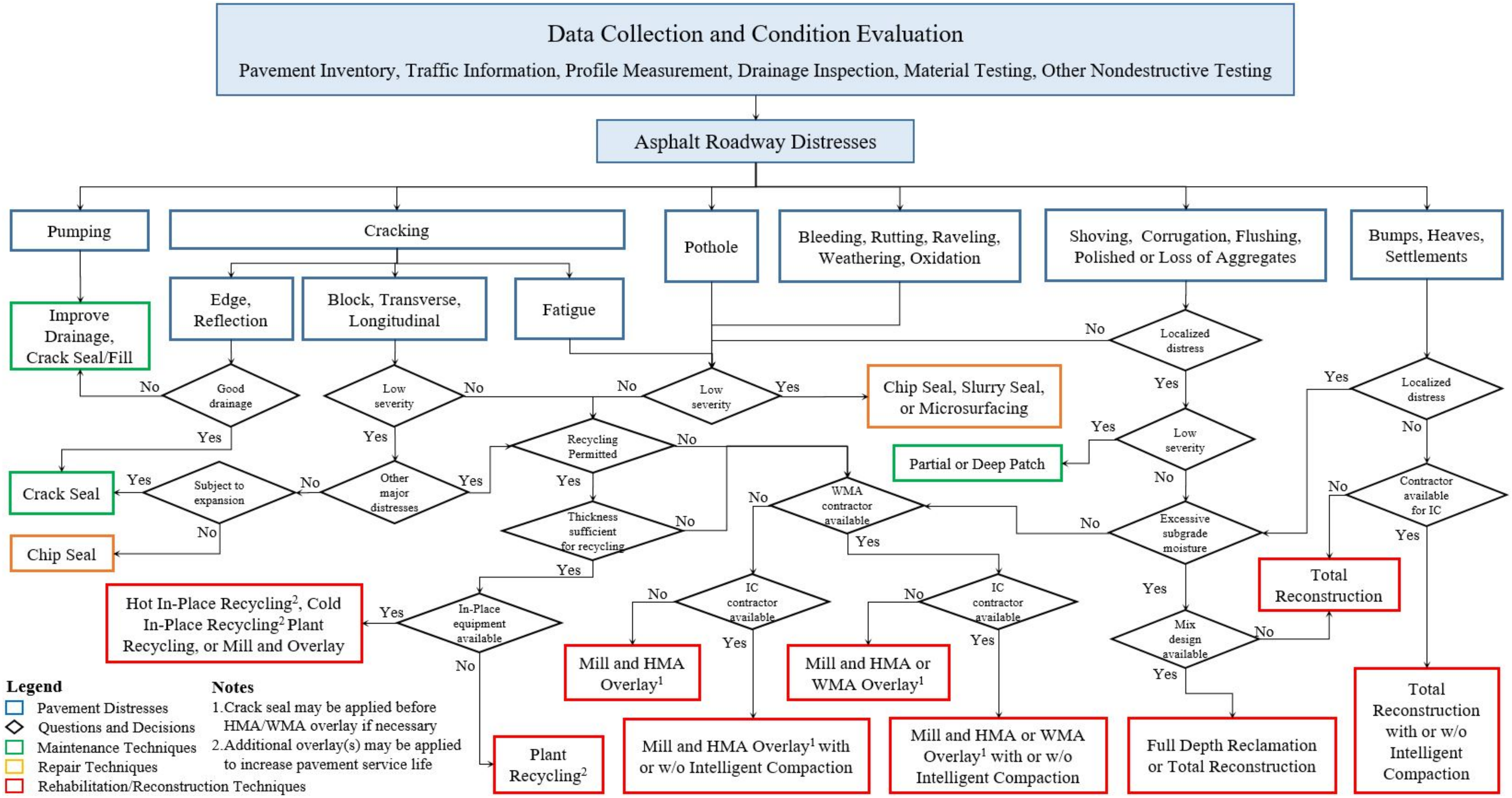
The research team developed (1) a qualitative MRR technique selection model in the form of a decision tree with comprehensive coverage of both traditional and innovative MRR techniques and (2) quantitative multi-criteria decision-making (MCDM) models featuring Fuzzy Analytical Hierarchy Process (FAHP) and Analytical Network Process (ANP). When used in conjunction, the qualitative and quantitative tools form an integrated decision support framework to identify the most appropriate MRR technique for an asphalt roadway. The qualitative model shortlists applicable MRR techniques, and these shortlisted alternatives are analyzed in the quantitative model to complete the evaluation process and generate MRR recommendations.

4.1 Decision Flowchart

The flowchart is generated based on decision trees and matrices used by state DOTs and best practices of the pavement management community. Although these decision trees and matrices exhibit great variation, in general they either form the connection between the causes of pavement distresses and MRR strategies, or define threshold values of pavement performance indicators (e.g. Ride Quality Index) to make MRR recommendations. Some tools also indicate the level of effectiveness of potential MRR alternatives for each type of distress. Due to the fact that many of the existing decision trees and matrices do not provide a comprehensive coverage of the innovative techniques, a new decision flowchart is proposed, as presented in Figure 15. This flowchart has been reviewed by officials in the New York State Department of Transportation (NYSDOT).

After data collection and condition evaluation of deficient roadway sections, appropriate MRR techniques are determined by: 1) identifying with the type of pavement distresses observed on site, and 2) answering descriptive questions as presented in the flowchart. Should the decision maker face challenges in answering any of the descriptive questions, it is recommended that all techniques that follow be considered in the next step (quantitative analysis).

Figure 15 Decision Flowchart for MRR Technique Selection



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

4.2 Multi-Criteria Decision Making Models

The quantitative component of the decision support framework uses Fuzzy Analytical Hierarchy Process (FAHP) and Analytical Network Process (ANP) to analyze shortlisted MRR alternatives based on the factors obtained from the survey in Table 18. As discussed before, FAHP provides an overall evaluation along with the ambiguity associated with the conclusion, while ANP is capable of taking into consideration the interdependencies among factors.

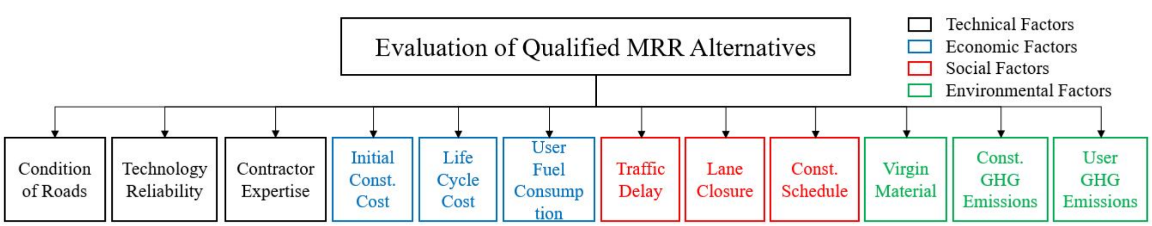
For both MCDM methods, the goal is to evaluate the shortlisted alternatives from the decision flowchart based on a set of technical, economic, social and environmental factors and find the most appropriate solution for the pavement distress to be addressed. Based on the survey of state departments of transportation, twelve factors are selected as criteria to evaluate the shortlisted alternatives under the overall goal.

4.2.1 Fuzzy Analytical Hierarchy Process Model

4.2.1.1 Hierarchical Structure

In AHP and FAHP, a hierarchical structure consists of criteria and sub-criteria and analysis is conducted in a "top-down" manner with multiple iterations of evaluation. In this research, however, in order to avoid complications during the execution of the surveys, all factors listed were treated as criteria for analysis and were then grouped into categories to reflect indications on a higher level, as shown in Figure 16.

Figure 16 Structure of Problem



4.2.1.2 Pairwise Comparison Matrix

The twelve factors are compared with each other in a pairwise format to determine their relative importance. The methodology of FAHP dictates that each factor features its importance rating in the form of a fuzzy set with multiple values, represented by the fuzzy memberships, and the relative importance value is also in the form of a fuzzy set instead of a crisp value. For ease of use and understanding, triangular fuzzy sets are selected for this study, where the medium value (m) is obtained as the average of importance rating for each factor, and the lower (l) and upper (u) values equal to the lower and upper boundaries of the 95% confidence interval using student's t-distribution, respectively.

As a result, values of fuzzy sets for each factor are obtained as listed in Table 20. The rating scale is the same as the one used in the survey, with 1 being the least important and 5 being the most important. Using the fuzzy sets, the relative importance is calculated and the pairwise comparison matrix is developed as shown in Figure 21.

Table 20 Importance Rating Fuzzy Sets for Factors affecting Decision Making

Factors Affecting Decision-Making	**Abbr.**	**Importance**
Condition of the Existing Road	CER	(3.69, 4.16, 4.64)
Construction GHG Emissions	CGE	(1.64, 2.03, 2.42)
Construction Schedule	CS	(3.00, 3.26, 3.52)
Contractor Availability	CA	(4.25, 4.33, 4.42)
Initial Construction Costs	ICC	(3.85, 4.23, 4.60)
Lane Closures	LC	(3.24, 3.61, 3.98)
Life Cycle Costs	LCC	(3.76, 4.10, 4.44)
Technical Reliability	TR	(3.65, 4.00, 4.35)
Traffic Delays	TD	(3.31, 3.68, 4.04)
User Fuel Consumption	UFC	(1.43, 1.84, 2.24)
User GHG Emissions	UGE	(1.46, 1.84, 2.22)
Virgin Materials Used	VMU	(2.65, 2.94, 3.22)

Table 21 FAHP Pairwise Comparison Matrix

	CER			**CGE**			**CS**			**CA**			**ICC**			**LC**			**LCC**			**TR**			**TD**			**UFC**			**UGE**			**VMU**		
CER	1	1	1	1.52	2.05	2.82	1.05	1.28	1.55	0.83	0.96	1.09	0.80	0.98	1.20	0.93	1.15	1.43	0.83	1.02	1.23	0.85	1.04	1.27	0.91	1.13	1.40	1.64	2.26	3.23	1.66	2.26	3.18	1.15	1.42	1.75
CGE	0.35	0.49	0.66	1	1	1	0.47	0.62	0.81	0.37	0.47	0.57	0.36	0.48	0.63	0.41	0.56	0.75	0.37	0.50	0.64	0.38	0.51	0.66	0.41	0.55	0.73	0.73	1.11	1.69	0.74	1.11	1.66	0.51	0.69	0.91
CS	0.65	0.78	0.95	1.24	1.60	2.14	1	1	1	0.68	0.75	0.83	0.65	0.77	0.91	0.75	0.90	1.09	0.68	0.80	0.94	0.69	0.81	0.96	0.74	0.89	1.06	1.34	1.77	2.45	1.35	1.77	2.41	0.93	1.11	1.33
CA	0.92	1.04	1.20	1.76	2.13	2.69	1.21	1.33	1.47	1	1	1	0.92	1.03	1.15	1.07	1.20	1.36	0.96	1.06	1.18	0.98	1.08	1.21	1.05	1.18	1.33	1.90	2.36	3.08	1.92	2.36	3.03	1.32	1.48	1.66
ICC	0.83	1.02	1.25	1.59	2.08	2.80	1.10	1.30	1.53	0.87	0.98	1.08	1	1	1	0.97	1.17	1.42	0.87	1.03	1.22	0.89	1.06	1.26	0.95	1.15	1.39	1.72	2.30	3.21	1.74	2.30	3.15	1.20	1.44	1.73
LC	0.70	0.87	1.08	1.34	1.78	2.43	0.92	1.11	1.33	0.73	0.83	0.94	0.71	0.85	1.03	1	1	1	0.73	0.88	1.06	0.75	0.90	1.09	0.80	0.98	1.20	1.45	1.96	2.78	1.46	1.96	2.73	1.01	1.23	1.50
LCC	0.81	0.98	1.20	1.55	2.02	2.70	1.07	1.26	1.48	0.85	0.95	1.04	0.82	0.97	1.15	0.94	1.13	1.37	1	1	1	0.86	1.02	1.22	0.93	1.11	1.34	1.67	2.23	3.09	1.69	2.23	3.04	1.17	1.40	1.67
TR	0.79	0.96	1.18	1.51	1.97	2.65	1.04	1.23	1.45	0.83	0.92	1.02	0.79	0.95	1.13	0.92	1.11	1.34	0.82	0.98	1.16	1	1	1	0.90	1.09	1.31	1.63	2.18	3.03	1.64	2.18	2.98	1.13	1.36	1.64
TD	0.71	0.88	1.10	1.37	1.81	2.46	0.94	1.13	1.35	0.75	0.85	0.95	0.72	0.87	1.05	0.83	1.02	1.25	0.75	0.90	1.08	0.76	0.92	1.11	1	1	1	1.48	2.00	2.82	1.49	2.00	2.77	1.03	1.25	1.52
UFC	0.31	0.44	0.61	0.59	0.90	1.37	0.41	0.56	0.75	0.32	0.42	0.53	0.31	0.44	0.58	0.36	0.51	0.69	0.32	0.45	0.60	0.33	0.46	0.61	0.35	0.50	0.68	1	1	1	0.65	1.00	1.54	0.45	0.63	0.85
UGE	0.31	0.44	0.60	0.60	0.90	1.35	0.41	0.56	0.74	0.33	0.42	0.52	0.32	0.44	0.58	0.37	0.51	0.68	0.33	0.45	0.59	0.34	0.46	0.61	0.36	0.50	0.67	0.65	1.00	1.55	1	1	1	0.45	0.63	0.84
VMU	0.57	0.71	0.87	1.10	1.44	1.96	0.75	0.90	1.07	0.60	0.68	0.76	0.58	0.69	0.83	0.67	0.81	0.99	0.60	0.72	0.86	0.61	0.73	0.88	0.66	0.80	0.97	1.18	1.60	2.24	1.20	1.60	2.21	1	1	1

Relative importance in the form of fuzzy sets are calculated based on equation (4). Taking the relative importance fuzzy sets of CER/TR as an example:

$$a_{CER/TR} = \frac{(3.69, 4.16, 4.64)}{(3.65, 4.00, 4.35)} = \left(\frac{3.69}{4.35}, \frac{4.16}{4.00}, \frac{4.64}{3.65}\right) = (0.85, 1.04, 1.27)$$

Once the matrix is set up, estimated weights for all factors are calculated using the Average of Normalized Column method, which includes the following steps:

- Add each element in the column
- Divide each element by its column total to obtain the normalized matrix (Table 22)
- Add the elements of rows of the normalized matrix
- Find the average of the normalized columns as the estimated weights
- Obtain estimated weights for each factor in fuzzy sets (Table 23).

Table 22 Normalized Pairwise Comparison Matrix

	CER	CGE	CS	CA	ICC	LC	LCC	TR	TD	UFC	UGE	VMU
CER	0.09 0.10 0.13	0.06 0.10 0.19	0.07 0.10 0.15	0.08 0.10 0.13	0.07 0.10 0.15	0.07 0.10 0.16	0.07 0.10 0.15	0.07 0.10 0.15	0.07 0.10 0.15	0.05 0.10 0.20	0.06 0.10 0.19	0.07 0.10 0.15
CGE	0.03 0.05 0.08	0.04 0.05 0.07	0.03 0.05 0.08	0.04 0.05 0.07	0.03 0.05 0.08	0.03 0.05 0.08	0.03 0.05 0.08	0.03 0.05 0.08	0.03 0.05 0.08	0.02 0.05 0.10	0.02 0.05 0.10	0.03 0.05 0.08
CS	0.06 0.08 0.12	0.05 0.08 0.14	0.07 0.08 0.10	0.07 0.08 0.10	0.06 0.08 0.11	0.06 0.08 0.12	0.06 0.08 0.11	0.06 0.08 0.11	0.06 0.08 0.12	0.04 0.08 0.15	0.05 0.08 0.15	0.06 0.08 0.12
CA	0.08 0.11 0.15	0.07 0.11 0.18	0.08 0.11 0.14	0.10 0.11 0.12	0.08 0.11 0.14	0.08 0.11 0.15	0.08 0.11 0.14	0.08 0.11 0.14	0.08 0.11 0.15	0.06 0.11 0.19	0.06 0.11 0.18	0.08 0.11 0.15
ICC	0.07 0.11 0.16	0.06 0.11 0.18	0.08 0.11 0.15	0.08 0.11 0.13	0.09 0.11 0.13	0.07 0.11 0.15	0.08 0.11 0.15	0.07 0.11 0.15	0.07 0.11 0.15	0.06 0.11 0.20	0.06 0.11 0.19	0.07 0.11 0.15
LC	0.06 0.09 0.14	0.05 0.09 0.16	0.06 0.09 0.13	0.07 0.09 0.11	0.06 0.09 0.13	0.07 0.09 0.11	0.06 0.09 0.13	0.06 0.09 0.13	0.06 0.09 0.13	0.05 0.09 0.17	0.05 0.09 0.17	0.06 0.09 0.13
LCC	0.07 0.10 0.15	0.06 0.10 0.18	0.07 0.10 0.14	0.08 0.10 0.13	0.07 0.10 0.14	0.07 0.10 0.15	0.09 0.10 0.12	0.07 0.10 0.14	0.07 0.10 0.15	0.06 0.10 0.19	0.06 0.10 0.18	0.07 0.10 0.15
TR	0.07 0.10 0.15	0.06 0.10 0.17	0.07 0.10 0.14	0.08 0.10 0.13	0.07 0.10 0.14	0.07 0.10 0.15	0.07 0.10 0.14	0.08 0.10 0.12	0.07 0.10 0.14	0.05 0.10 0.19	0.06 0.10 0.18	0.07 0.10 0.14
TD	0.06 0.09 0.14	0.05 0.09 0.16	0.06 0.09 0.13	0.07 0.09 0.12	0.06 0.09 0.13	0.06 0.09 0.14	0.06 0.09 0.13	0.06 0.09 0.13	0.08 0.09 0.11	0.05 0.09 0.17	0.05 0.09 0.17	0.06 0.09 0.13
UFC	0.03 0.05 0.08	0.02 0.05 0.09	0.03 0.05 0.07	0.03 0.05 0.06	0.03 0.05 0.07	0.03 0.05 0.08	0.03 0.05 0.07	0.03 0.05 0.07	0.03 0.05 0.07	0.03 0.05 0.06	0.02 0.05 0.09	0.03 0.05 0.07
UGE	0.03 0.05 0.08	0.02 0.05 0.09	0.03 0.05 0.07	0.03 0.05 0.06	0.03 0.05 0.07	0.03 0.05 0.07	0.03 0.05 0.07	0.03 0.05 0.07	0.03 0.05 0.07	0.02 0.05 0.09	0.03 0.05 0.06	0.03 0.05 0.07
VMU	0.05 0.07 0.11	0.04 0.07 0.13	0.05 0.07 0.10	0.06 0.07 0.09	0.05 0.07 0.10	0.05 0.07 0.11	0.05 0.07 0.10	0.05 0.07 0.10	0.05 0.07 0.11	0.04 0.07 0.14	0.04 0.07 0.13	0.06 0.07 0.09

Table 23 Estimated Weights of Factors Affecting Decision Making

Factors Affecting Decision-Making	Abbr.	Estimated Weights
Condition of the Existing Road	CER	(0.069, 0.104, 0.158)
Construction GHG Emissions	CGE	(0.031, 0.051, 0.081)
Construction Schedule	CS	(0.056, 0.081, 0.121)
Contractor Availability	CA	(0.078, 0.108, 0.153)
Initial Construction Costs	ICC	(0.072, 0.106, 0.158)
Lane Closures	LC	(0.056, 0.081, 0.121)
Life Cycle Costs	LCC	(0.070, 0.102, 0.152)
Technical Reliability	TR	(0.068, 0.100, 0.149)
Traffic Delays	TD	(0.062, 0.092, 0.138)
User Fuel Consumption	UFC	(0.027, 0.046, 0.075)
User GHG Emissions	UGE	(0.028, 0.046, 0.074)
Virgin Materials Used	VMU	(0.050, 0.073, 0.110)

4.2.1.3 Consistency of the Pairwise Comparison Matrix

The positive reciprocal matrix is identified as "not consistent" if the Maximum Eigen Value (λ_{max}) is larger than the order of the matrix (n). Consistency of the matrix is measured by the consistency index (CI) and consistency ratio (CR), which are calculated using the following equations (Saaty 1980):

$$Consistency\ Index = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

$$Consistency\ Ratio = \frac{Consistency\ Index}{Random\ Index} \quad (6)$$

If the matrix is perfectly consistent, CI and CR should both equal to zero. However, for AHP, the pairwise comparison matrix does not necessarily need to be perfectly consistent. As long as CR is not greater than 0.10, the matrix is considered sufficiently consistent. It is noteworthy, though, that a pairwise comparison matrix with a greater CR value is expected to generate more inconsistent conclusions. Saaty (1980) estimated Random Index values for various matrix sizes and these values are listed in Table 24.

Table 24 Random Index for Matrix Size 3 to 12

Matrix Size	3	4	5	6	7	8	9	10	11	12
Random Index	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

Source: Saaty (1980)

To calculate the CR for the pairwise comparison matrix, a de-fuzzification process is adopted using the Program Evaluation and Review Technique (PERT) to transform fuzzy sets into crisp values. As a widely used estimation tool, PERT uses three values from optimistic scenario, pessimistic scenario, and most likely scenario to find a weighted average for specific tasks, which features similar characteristics of triangular fuzzy sets. The de-fuzzied pairwise comparison matrix used in examining the consistency is shown in Table 25. The Maximum Eigen Value (λ_{max}) is calculated through:

- Finding average of each row;
- Dividing each element by its column total to obtain the normalized matrix;
- Multiplying the de-fuzzied matrix with the normalized matrix to get a new matrix;
- Dividing elements in the new matrix by those in the normalized matrix and obtaining the maximum value as (λ_{max})

Table 25 De-fuzzied Pairwise Comparison Matrix

	CER	CGE	CS	CA	ICC	LC	LCC	TR	TD	UFC	UGE	VMU
CER	1.00	2.09	1.28	0.96	0.99	1.16	1.02	1.05	1.14	2.32	2.32	1.43
CGE	0.49	1.00	0.63	0.47	0.48	0.57	0.50	0.51	0.56	1.14	1.14	0.70
CS	0.79	1.63	1.00	0.75	0.77	0.91	0.80	0.82	0.89	1.81	1.81	1.12
CA	1.05	2.16	1.33	1.00	1.03	1.20	1.06	1.09	1.18	2.40	2.40	1.48
ICC	1.02	2.12	1.30	0.98	1.00	1.18	1.04	1.06	1.16	2.35	2.35	1.45
LC	0.88	1.81	1.11	0.83	0.86	1.00	0.89	0.91	0.99	2.01	2.01	1.24
LCC	0.99	2.05	1.26	0.95	0.97	1.14	1.00	1.03	1.12	2.28	2.27	1.40
TR	0.97	2.00	1.23	0.92	0.95	1.11	0.98	1.00	1.09	2.23	2.22	1.37
TD	0.89	1.84	1.13	0.85	0.88	1.02	0.90	0.92	1.00	2.05	2.04	1.26
UFC	0.45	0.93	0.57	0.42	0.44	0.51	0.45	0.46	0.51	1.00	1.03	0.63
UGE	0.45	0.93	0.57	0.42	0.44	0.51	0.45	0.46	0.51	1.03	1.00	0.63
VMU	0.71	1.47	0.91	0.68	0.70	0.82	0.72	0.74	0.80	1.64	1.63	1.00

Based on Equations (5) and (6), it is calculated that CI = 0.011 and CR = 0.007. Therefore, the pairwise comparison matrix proves to be in good consistency, and the estimated weights shown in Table 21 can be used to evaluate alternatives in the decision support tool.

4.2.2 Analytical Network Process

As discussed before, Analytical Network Process (ANP) excels among other commonly used MCDM methods due to its ability in modeling interdependencies between elements. In this study, interdependencies between twelve factors are categorized into four levels based on magnitude of influence, and priorities are calculated following the general steps of ANP.

4.2.2.1 Pairwise Comparison Matrix

Based on the algorithms of ANP, a pairwise comparison matrix (Table 26) is developed using the values from Table 18. Following similar steps as in FAHP, normalized weights for each factor (Table 27) are obtained through a weighted pairwise comparison matrix.

4.2.2.2 Interdependency

In order to model interdependencies, A pairwise influence matrix is developed, as shown in Table 28, in which each cell in the matrix shows the magnitude of influence from the factor at that particular row (on the left) on the factor at that particular column (on the top).

For any 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. This can be explained using the example of User Fuel Consumption and User Greenhouse Gas Emissions. The former factor has very strong influence on the latter, but the latter does not have a discernible impact on the former.

Table 26 Pairwise Comparison Matrix for ANP

	CER	CGE	CS	CA	ICC	LC	LCC	TR	TD	UFC	UGE	VMU
CER	1	2.05	1.28	0.96	0.98	1.15	1.02	1.04	1.13	2.26	2.26	1.42
CGE	0.49	1	0.62	0.47	0.48	0.56	0.50	0.51	0.55	1.11	1.11	0.69
CS	0.78	1.60	1	0.75	0.77	0.90	0.80	0.81	0.89	1.77	1.77	1.11
CA	1.04	2.13	1.33	1	1.03	1.20	1.06	1.08	1.18	2.36	2.36	1.48
ICC	1.02	2.08	1.30	0.98	1	1.17	1.03	1.06	1.15	2.30	2.30	1.44
LC	0.87	1.78	1.11	0.83	0.85	1	0.88	0.90	0.98	1.96	1.96	1.23
LCC	0.98	2.02	1.26	0.95	0.97	1.13	1	1.02	1.11	2.23	2.23	1.40
TR	0.96	1.97	1.23	0.92	0.95	1.11	0.98	1	1.09	2.18	2.18	1.36
TD	0.88	1.81	1.13	0.85	0.87	1.02	0.90	0.92	1	2.00	2.00	1.25
UFC	0.44	0.90	0.56	0.42	0.44	0.51	0.45	0.46	0.50	1	1.00	0.63
UGE	0.44	0.90	0.56	0.42	0.44	0.51	0.45	0.46	0.50	1.00	1	0.63
VMU	0.71	1.44	0.90	0.68	0.69	0.81	0.72	0.73	0.80	1.60	1.60	1

Table 27 Normalized Weights for ANP

Factors Affecting Decision-Making	Average Ratings
Condition of the Existing Road	0.104
Construction GHG Emissions	0.051
Construction Schedule	0.081
Contractor Availability	0.108
Initial Construction Costs	0.106
Lane Closures	0.09
Life Cycle Costs	0.102
Technical Reliability	0.1
Traffic Delays	0.092
User Fuel Consumption	0.046
User GHG Emissions	0.046
Virgin Materials Used	0.073

In ANP algorithm, interdependencies of elements are modeled by comparing the levels of influences of two elements on a control element. In order to generate ratings of inter-factor influence that can be utilized by ANP, Table 29 is developed using a similar ratio scale to conventional AHP/ANP paradigm. For each factor as a control criterion, two other factors are compared; the relative importance is determined and fed into an interdependency pairwise comparison matrix. Therefore, twelve interdependency pairwise comparison matrices of size eleven by eleven are developed.

Table 28 Pairwise Influence Matrix

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 29 Pairwise Comparison Rating for 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 two other criteria's influence on this criterion. A publicly accessible software, "Super Decision", is used in the remaining steps of calculation. In Super Decision, the pairwise comparison of inter-factor influence is presented in multiple ways including graphical, verbal, matrix, questionnaire, and direct; and instead of reciprocals, the ratings of pairwise inter-factor influence are presented by the same value with colorific distinction, shown in Table 30. The unweighted supermatrix of factors in Super Decision is presented in Table 31.

Table 30 Pairwise Comparison Rating of Influence in Super Decision

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

Table 31 Supermatrix of Criteria

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

With interdependencies taken into consideration, priorities of the twelve factors using ANP algorithm are then calculated in Super Decision and the results are shown in Table 32. In comparison to the weights obtained in FAHP, ANP places higher emphasis on factors with more profound impacts on other factors (e.g. Condition of the Existing Road and Construction Schedule). These weights are used to evaluate alternatives in the decision support tool.

Table 32 Estimated Priorities by ANP

Factors Affecting Decision-Making	Estimated Priorities
Condition of the Existing Road	0.094
Construction GHG Emissions	0.050
Construction Schedule	0.106
Contractor Availability	0.128
Initial Construction Costs	0.067
Lane Closures	0.101
Life Cycle Costs	0.057
Technical Reliability	0.115
Traffic Delays	0.080
User Fuel Consumption	0.072
User GHG Emissions	0.056
Virgin Materials Used	0.073

4.2.3 Evaluation of Alternatives

To perform project-specific analysis of alternatives, the shortlisted MRR techniques are compared in a pairwise manner based on the twelve criteria. Users evaluate the relative importance between the two alternatives for each criterion. As a result, twelve comparison matrices are generated and then multiplied with estimated weights. The summation of ratings represents the overall score for the alternative. These processes apply to both FAHP and ANP methods. However, in FAHP, the ratings and scores are in the form of fuzzy sets, while in ANP ratings and scores are represented with crisp values.

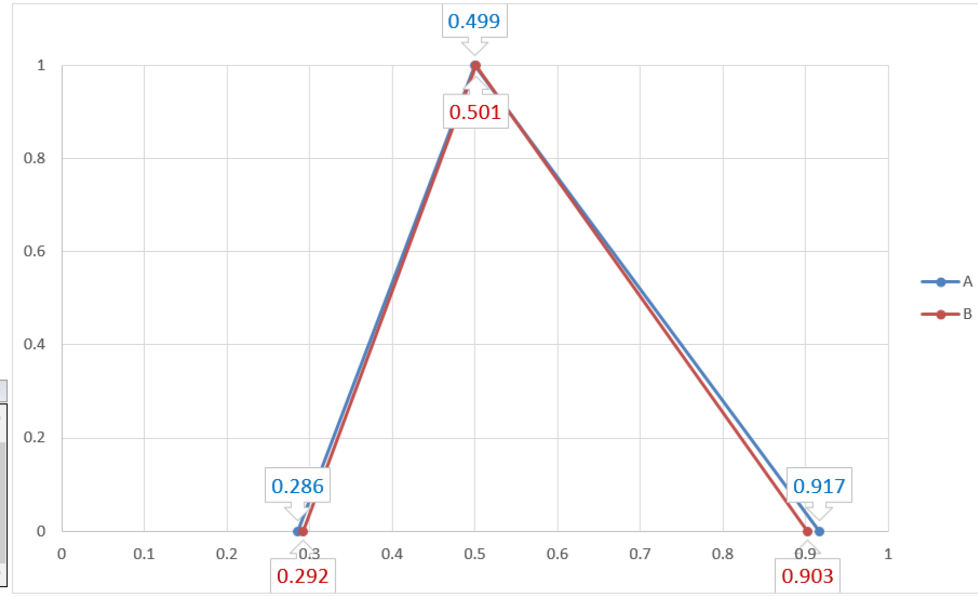
For ease of use, the calculation procedures and pairwise comparisons have been set up in a spreadsheet program with drop-down menu options for the selection of relative importance values. The spreadsheet tool consists of “Introduction”, “Evaluation”, “Factors”, and “Matrices” sheets. Decision makers use the “Evaluation” sheet, as shown in Figure 17, to enter relative importance values. “Factors” sheet contains the estimated weights (based on the survey results) used by FAHP and ANP, and “Matrices” sheet contains equations and values used in calculations.

Figure 17 Decision Support Tool Interface of Alternative Evaluation

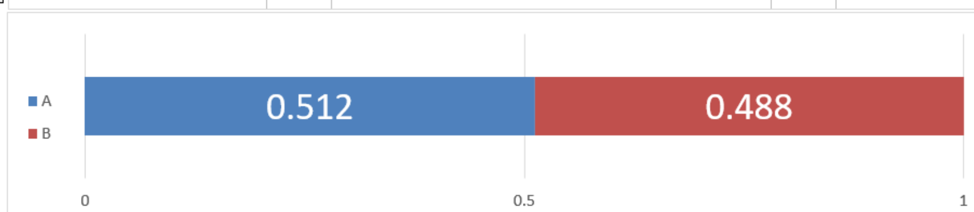
Evaluation Question: Regarding Each Criterion, How is Milling and Overlay (A) Compared to CIR (B)?	
Criteria	**A vs B?**
Condition of the Existing Road	Equally Favorable
Technical Reliability	Fairly Superior
Contractor Availability	Fairly Inferior
Initial Construction Costs	Weakly Inferior
Life Cycle Costs	Equally Favorable
User Fuel Consumption*	
Traffic Delays**	
Lane Closures	
Construction Schedule	
Virgin Materials Used	Weakly Inferior
Construction GHG Emissions	Weakly Superior
User GHG Emissions	Weakly Superior

Strongly Inferior
Fairly Inferior
Weakly Inferior
Equally Favorable
Weakly Superior
Fairly Superior
Strongly Superior
Absolutely Superior

Note
**Refers to the additional user fuel cost due to project execution
**Refers to local traffic delays due to project execution



Fuzzy Analytical Hierarchy Process (FAHP) Output



Analytical Network Process (ANP) Output

Table 33 provides values corresponding to the various relative importance categories on a scale of 1 to 9. It should be noted that in FAHP, the 1 to 5 scale used by van Laarhoven and Pedrycz (1983) and Chang (1996) was not adopted in this research due to the limitations it may present in capturing the difference when one alternative is weakly superior or inferior to the other and also to ensure uniformity with the ANP method.

Table 33 Rating Scheme for Alternative Pairwise Comparison

Pairwise Comparison Rating Scheme		
Result	**FAHP**	**ANP**
Absolutely Inferior	(0.111, 0.111, 0.111)	1/9
Strongly Inferior	(0.125, 0.143, 0.167)	1/7
Fairly Inferior	(0.167, 0.200, 0.250)	1/5
Weakly Inferior	(0.250, 0.333, 0.500)	1/3
Equally Favorable	(1, 1, 1)	1
Weakly Superior	(2, 3, 4)	3
Fairly Superior	(4, 5, 6)	5
Strongly Superior	(6, 7, 8)	7
Absolutely Superior	(9, 9, 9)	9

As seen in Figure 17, after the overall scores for the two alternatives are calculated, results for FAHP are displayed in the form of fuzzy membership functions at the top-right side of the interface to indicate the ambiguity of conclusion. Results for ANP are displayed in a bar chart format at the lower right side of the interface. For both methods, the alternative with the higher score is considered to be more appropriate for the project. For FAHP, a higher degree of overlap between the two alternatives indicates a higher level of ambiguity in the conclusion. In situations where the two methods generate contradicting results, as shown in Figure 17, a recommendation can be made for either method using expert judgment, as the two alternatives being evaluated are highly comparable with negligible differences. This decision support tools have also been reviewed by a group of NYSDOT officials.

5 CASE STUDIES AND VALIDATION

The research team examined information provided in *NYSDOT's Pavement Data Report* to select asphalt roadway MRR projects completed in the recent years. As a result of this process, two projects in Onondaga County, New York, are selected in order to validate the decision support framework developed in this study.

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 solutions. The agreement between the course of action proposed by the framework and the actual technique 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 in pilot projects. Therefore, documentation on projects in which these two techniques are used was limited.

5.1 Case Study 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 AADT of 79,504 and a v/c ratio of 0.89 at the time of project execution.

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 greenhouse gas (GHG) emissions. CIR also uses lower amounts of virgin materials and creates lower levels of construction GHG emissions. The expected life cycle cost for CIR is also lower than that for milling and overlay.

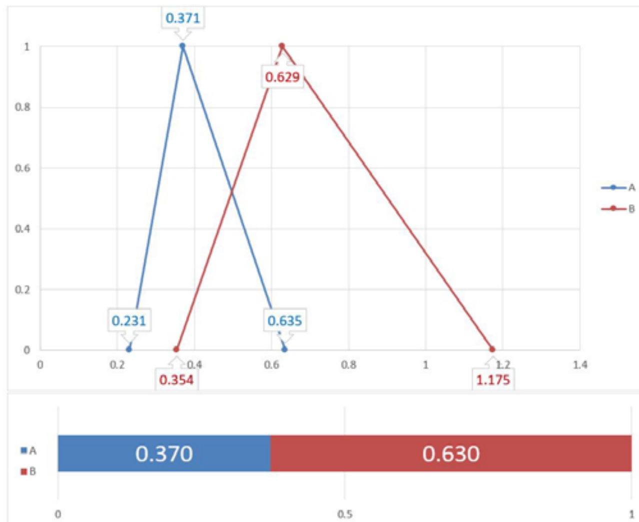
Figure 18 shows the output of the decision tools with the information presented above entered as inputs. Both methods have ruled alternative B, CIR, as the recommended technique for this project. According to the FAHP output, the small overlapping area for the two alternatives indicates a low level of ambiguity. This conclusion coincides with the actual course of action followed by NYSDOT (NYSDOT 2012).

Figure 18 Decision Support Tool Modeling Results for I-81 Project

Evaluation Question: Regarding Each Criterion, How is Milling and Overlay (A) Compared to CIR (B)?

Criteria	A vs B?
Condition of the Existing Road	Equally Favorable
Technical Reliability	Equally Favorable
Contractor Availability	Equally Favorable
Initial Construction Costs	Equally Favorable
Life Cycle Costs	Weakly Inferior
User Fuel Consumption*	Weakly Inferior
Traffic Delays**	Weakly Inferior
Lane Closures	Equally Favorable
Construction Schedule	Weakly Inferior
Virgin Materials Used	Fairly Inferior
Construction GHG Emissions	Weakly Inferior
User GHG Emissions	Weakly Inferior

Note
**Refers to the additional user fuel cost due to project execution
**Refers to local traffic delays due to project execution



5.2 Case Study 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 v/c ratio of 0.5 in 2015. The subbase was unstabilized.

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.

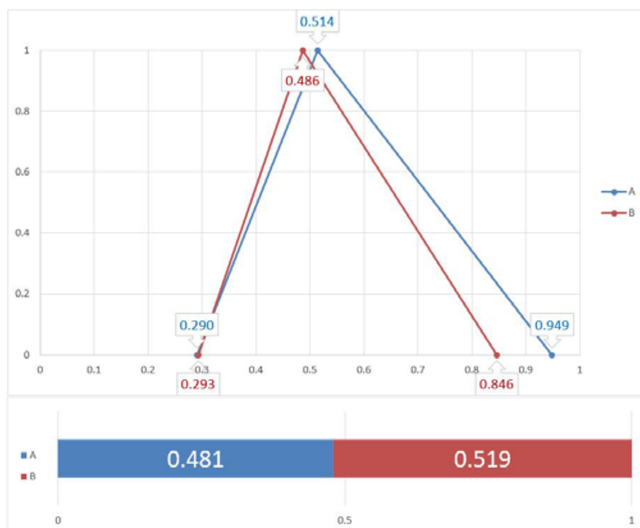
Figure 19 shows the output of the decision tools with the information presented above entered as inputs. There is considerable disagreement between FAHP and ANP modeling results, as FAHP favors FDR, while ANP favors total reconstruction. This is because ANP assigns higher weights to technical reliability and contractor availability, where total reconstruction prevails. Considering the large overlap between the alternatives in FAHP output, the final FAHP recommendation features a high level of ambiguity. Therefore, it can be concluded that both techniques are appropriate candidates for this project. The output of the ANP model is in alignment with NYSDOT's actual course of action (NYSDOT 2015).

Figure 19 Decision Support Tool Modeling Results for RT 11 Project

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

Criteria	A vs B?
Condition of the Existing Road	Equally Favorable
Technical Reliability	Fairly Inferior
Contractor Availability	Fairly Inferior
Initial Construction Costs	Weakly Superior
Life Cycle Costs	Weakly Superior
User Fuel Consumption*	Equally Favorable
Traffic Delays**	Equally Favorable
Lane Closures	Equally Favorable
Construction Schedule	Equally Favorable
Virgin Materials Used	Weakly Superior
Construction GHG Emissions	Weakly Superior
User GHG Emissions	Equally Favorable

Note
**Refers to the additional user fuel cost due to project execution
**Refers to local traffic delays due to project execution



6 CONCLUSIONS AND FUTURE RESEARCH

In order to fulfill the research objectives, a comprehensive literature review and a nationwide survey on innovative asphalt roadway MRR techniques were conducted. In light of the collected information, important factors that affect the decision-making processes in selecting appropriate MRR techniques were identified. A decision support framework consisting of a decision flowchart and two multi-criteria decision models were developed. The purpose of this framework is to provide transportation agencies with both qualitative and quantitative tools to be used in making decisions regarding appropriate MRR techniques for asphalt roadways. Case studies in the State of New York have shown that the proposed decision support framework is capable of providing quantitative recommendations in agreement with the actual practices.

Future research may focus on the following aspects:

- Fine-tune the default weights and priorities of different criteria;
- Incorporate additional criteria such as work zone / user safety;
- Provide functionality that allows certain criteria to be removed from evaluation; and
- Expand the spreadsheet to allow evaluation of more than two alternatives at a time.

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APPENDIX I - SURVEY FORM

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 maintenance, repair, and reconstruction (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. Please comment on the challenges your agency has faced while employing an innovative MRR 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 - SUMMARY OF SURVEY OF CANADIAN PROVINCES

Provinces that responded the survey:

Alberta (AB), British Columbia (BC), Ontario (ON), and Saskatchewan (SK)

Question 1 and 2: Traditional maintenance, repair, and reconstruction (MRR) methods used and the amount of work completed for asphalt roadways in the last five years.

Traditional Techniques	Provinces			
	AB	BC	ON	SK
Chip Seal	500	Unknown	15	71
Crack Seal	582	Unknown	Unknown	137
Scrub Seal				
Slurry Seal	25	Unknown	53	
HMA Overlay	3700	Unknown	700	180
Total Reconstruction		Unknown	135	
Other		HIPR		Microsurfacing

*Amount of work in miles/year for Crack Seal and lane-miles/year for the other techniques

Question 3: Innovative maintenance, repair, and reconstruction (MRR) methods used

Innovative Techniques	Provinces			
	AB	BC	ON	SK
Warm Mix Asphalt Overlay	√	√	√	√
Asphalt Full Depth Reclamation	√	√	√	
Asphalt Partial Depth Reclamation		√		
Reclaimed Asphalt Pavement	√	√	√	√
Cold In Place Recycling	√		√	
Intelligent Compaction				
Innovative Soil Stabilization	√	√		√
Others: HIPR		√		

Question 4: Planned pilot projects on Innovative methods

Provinces	Provinces			
	AB	BC	ON	SK
Innovative Methods	Intelligent Compaction, Geo-cell		Precast concrete in-lay on asphalt pavement	Cold in-place recycling, fiber reinforcement for asphalt mixes

Question 5b: Characteristics of Innovative methods

Average Miles/year	Provinces			
	AB	BC	ON	SK
Warm Mix Asphalt Overlay	Unknown	Unknown	200	
Asphalt Full Depth Reclamation	37	Unknown	135	
Asphalt Partial Depth Reclamation		Unknown		
Reclaimed Asphalt Pavement	Unknown	Unknown	619000	Unknown
Cold In Place Recycling	12		83	
Intelligent Compaction				
Innovative Soil Stabilization				Limited
Others: HIPR		Unknown		

Cost	Provinces			
	AB	BC	ON	SK
Warm Mix Asphalt Overlay	Unknown	Unknown	$110/t	
Asphalt Full Depth Reclamation	$20 / m2	Unknown	$1.5/ m2	
Asphalt Partial Depth Reclamation		Unknown		
Reclaimed Asphalt Pavement	Unknown	Unknown		n/a
Cold In Place Recycling	$10/m2		$10/m2	
Intelligent Compaction				
Innovative Soil Stabilization				n/a
Others: HIPR		Unknown		

Expected Service Life	Provinces			
	AB	BC	ON	SK
Warm Mix Asphalt Overlay	20	18 to 22	Same 15	
Asphalt Full Depth Reclamation	20	18 to 22	10 to 17	
Asphalt Partial Depth Reclamation		18 to 22		
Reclaimed Asphalt Pavement	20	18 to 22		15
Cold In Place Recycling	14 to 18		10 to 17	
Intelligent Compaction				
Innovative Soil Stabilization				n/a
Others: HIPR		12 to 16		

Construction Time	Provinces			
	AB	BC	ON	SK
Warm Mix Asphalt Overlay		n/a	Same	
Asphalt Full Depth Reclamation		n/a		
Asphalt Partial Depth Reclamation		n/a		
Reclaimed Asphalt Pavement		n/a		2 months
Cold In Place Recycling				
Intelligent Compaction				
Innovative Soil Stabilization				n/a
Others: HIPR		n/a		

Question 6: General performance of Innovative MRR Projects

Performance Indicator	Provinces			
	AB	BC	ON	SK
On or ahead of schedule	100%	80%		
Within or below budget	100%	80%		
With acceptable quality and workmanship	100%	80%		80%
With no accident		100%		100%

Question 7: Rate importance of following factors in the decision making process

Factors affecting decision making	Provinces			
	AB	BC	ON	SK
Initial Construction Cost	4	4	4	5
Life Cycle Cost	4	4	5	3
Amount of Virgin Materials Used	2	5	4	1
Condition of Existing Road	5	4	5	4
Greenhouse gas emissions from construction	2	4	4	1
Construction schedule	3	5	4	4
Lane Closure	2	5	5	4
Traffic Delays	2	5	5	3
Greenhouse gas emissions from users	2	5	4	1
Fuel consumption of users	1	4	3	1

Question 8: Percentage of RAP used in MRR projects

RAP Percentage	Provinces			
	AB	BC	ON	SK
0-5%	√ (31% of projects)			
6-10%	√ (30% of projects)			
11-15%	√ (10% of projects)			
16-20%	√ (25% of projects)	√	√	√
21-25%	√ (3% of projects)			

26% or greater	1% (one project in 2014 used 28% of RAP content)			

Question 9: Challenges in employing innovative MRR techniques

Innovative Methods	Provinces			
	AB	BC	ON	SK
Warm Mix Asphalt Overlay			Cost, longevity	
Asphalt Full Depth Reclamation	Timeframe for construction	Cost	Existing pavement depth variation	
Asphalt Partial Depth Reclamation		Cost		
Reclaimed Asphalt Pavement	Inconsistency of material	Keep RAP below 25%	Quality	RAP materials not enough
Cold In Place Recycling			Existing material properties	
Intelligent Compaction			Machine availability	
Innovative Soil Stabilization				Cost. Material availability
Others: HIPR				Contractor availability

Question 10: Decision support systems (DSS) used or not

Provinces			
AB	BC	ON	SK
No DSS	Yes	No DSS	Yes, Vemax

APPENDIX III - MINUTES OF MEETING WITH NYSDOT OFFICIALS

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.

Topics and Discussions:

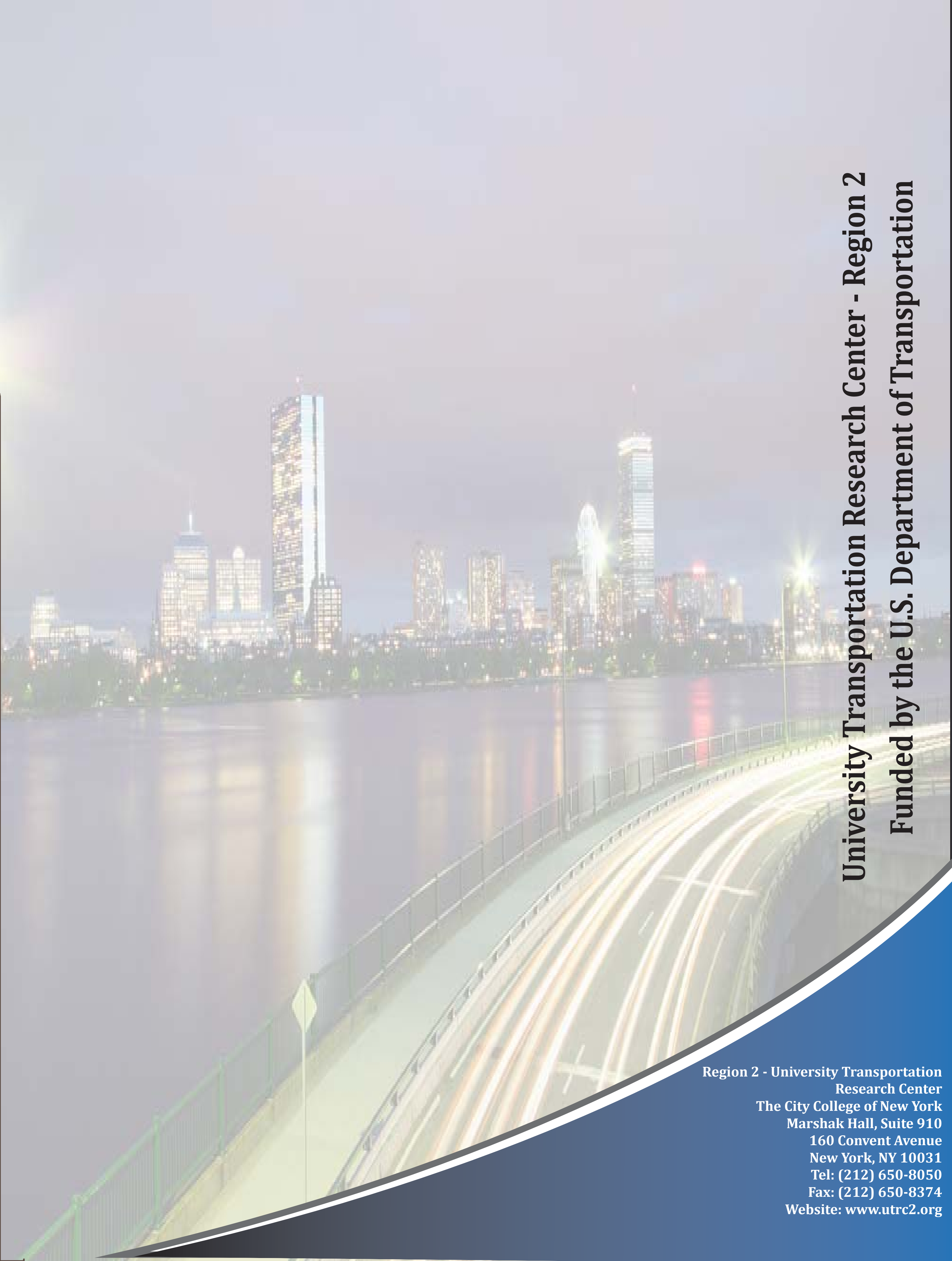
- General Guidelines and Practices of Pavement Preservation
    - The MRR processes described in the research are summarized as pavement preservation practices at NYSDOT/FHWA.
    - NYSDOT has "Sufficiency Data" for its pavement network uploaded on its website. In this dataset, pavement condition ratings (particularly related to rutting) are assigned based on the worst rating observed within a section of one or several miles, which may not give an accurate picture of the overall conditions of roadways
    - NYSDOT is switching to an enterprise level asset management system, with a focus on performance-based management systems for various infrastructure types. Tradeoffs among multiple infrastructure types (pavement, bridges, culverts, etc.) will be part of the transportation asset management plan (TAMP).
- Decision Making in Pavement Preservation Treatment Selection
    - The timing of these preservation practices has more influence on how the decisions are made, in comparison to the severity.
    - Currently, cost per lane mile is the most important indicator.
    - Making accurate benefit and cost analysis presents a major challenge, as results of these analyses can be extremely sensitive to even small variations in unit cost

and discount rate values. Accordingly, selecting amongst MRR techniques with varying levels of service life extensions is rather difficult. An example is choosing between using chip seal that lasts for 2 years or microsurfacing that last for 4 years. Another example is choosing between an asphalt and concrete overlay, where the first option is faster to build while the second option lasts longer.

  - Performance management is becoming more important, where 4 criteria are considered: ride quality (IRI or PSR), faulting (for rigid pavements), cracking, and rutting (for flexible pavements). These four indicators are driving the decision making process.
  - Public perception is another important aspect during the decision making process because the agency would like to ensure that the project will meet the expectations of the public when it is finished.
  - Asset management in local municipalities and counties is an important research area as 40 percent of the federal budget goes to these agencies. Treatment selection presents a major struggle because many local agencies do not have reliable sources to support decision making. Furthermore, high turnover rates at the decision-making levels hinder effective implementation of asset management procedures.
  - At the municipal and county levels, decisions on selection of treatment techniques are primarily made based on contractors' input.
- Information on Innovative MRR Techniques
  - Cold-In-Place Recycling (CIR) has been extensively used in the Northeast Region.
  - The decision in terms of selecting whether a WMA or an HMA overlay will be applied in a project is generally left to the contractor.
  - Currently, the RAP control plan mostly relies on the source of RAP to determine its quality. Usually, reclaimed asphalt used in DOT projects come from milling projects again undertaken in DOT projects. It is generally not allowed to use RAP from state roads on Interstate highways.
  - The only acknowledged benefit from Intelligent Compaction (IC) is the color-

coding feature showing well/poorly compacted areas.

- 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.
- Miscellaneous
    - There is research interest in tracking degradation / monitoring deterioration of pavements with respect to various levels of expenditure.



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