Iowa Pavement Asset Management Decision-Making Framework

Final Report
October 2015

CONSTRUCTION MANAGEMENT AND TECHNOLOGY

IOWA STATE UNIVERSITY
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16. Abstract

Most local agencies in Iowa currently make their pavement treatment decisions based on their limited experience due primarily to lack of a systematic decision-making framework and a decision-aid tool. The lack of objective condition assessment data of agency pavements also contributes to this problem.

This study developed a systematic pavement treatment selection framework for local agencies to assist them in selecting the most appropriate treatment and to help justify their maintenance and rehabilitation decisions. The framework is based on an extensive literature review of the various pavement treatment techniques in terms of their technical applicability and limitations, meaningful practices of neighboring states, and the results of a survey of local agencies. The treatment selection framework involves three different steps: pavement condition assessment, selection of technically feasible treatments using decision trees, and selection of the most appropriate treatment considering the return-on-investment (ROI) and other non-economic factors.

An Excel-based spreadsheet tool that automates the treatment selection framework was also developed, along with a standalone user guide for the tool. The Pavement Treatment Selection Tool (PTST) for Local Agencies allows users to enter the severity and extent levels of existing distresses and then, recommends a set of technically feasible treatments. The tool also evaluates the ROI of each feasible treatment and, if necessary, it can also evaluate the non-economic value of each treatment option to help determine the most appropriate treatment for the pavement.

It is expected that the framework and tool will help local agencies improve their pavement asset management practices significantly and make better economic and defensible decisions on pavement treatment selection.

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IOWA PAVEMENT ASSET MANAGEMENT DECISION-MAKING FRAMEWORK

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EXECUTIVE SUMMARY

Most local agency staff in Iowa currently make their pavement treatment decisions based on their experience and judgement due primarily to lack of a systematic decision-making framework and a decision-aid tool. Local agencies need a systematic pavement treatment selection framework to justify and easily defend maintenance and rehabilitation decisions and to achieve the highest return value on their pavement investment. Maintenance and rehabilitation decisions can be technically justified by incorporating pavement condition data into the decision-making framework. The highest return-on-investment (ROI) value can be determined by analyzing the economic values of technically feasible treatments.

This study first conducted a comprehensive literature review and documented various treatment methods available in the industry and their technical application boundaries, treatment costs, and expected life expectancies. In addition, pavement maintenance and rehabilitation selection practices were documented as part of the literature review. A statewide survey questionnaire was also sent out to determine common local pavement distress types, common treatment methods used by local agencies, and decision-making processes in selecting pavement treatments used by local agencies. In addition, follow-up phone calls and interviews were conducted. The findings from the literature review and the survey and interviews were incorporated into development of a pavement treatment selection framework for local agencies.

This project developed a pavement treatment selection framework for local agencies that considers common practices and limitations. The treatment selection framework consists of decision-making matrices and decision-making trees for both asphalt and Portland cement concrete pavements. The framework uses a novel pavement condition classification process based on the severity and extent level of existing pavement distresses. Three classes are defined for each pavement type. Each class indicates whether the pavement is heavily, moderately, or slightly deteriorated.

The framework provides decision trees to determine technically feasible treatments for different pavement condition classes. The decision-making logic considers roughness, friction, and distress distributions. The economic value of each technically feasible treatment is calculated using the equivalent uniform annual cost (EUAC) method and ROI. Non-economic values are also determined using the analytic hierarchy process (AHP).

Based on the pavement treatment selection framework, an Excel-based spreadsheet tool that automates the treatment selection process was also developed, along with a standalone user guide for the tool. The Pavement Treatment Selection Tool (PTST) for Local Agencies allows users to enter the existing distresses and it then recommends a set of technically feasible treatments.

The tool automatically calculates the EUAC and ROI values for each feasible treatment. Users can easily compare the economic values of feasible treatment options and then make an investment decision that yields the highest return. The tool has an option to allow users to input local treatment costs and service life data instead of using default values, which leads to more realistic results.

The spreadsheet tool also allows users to build future maintenance and rehabilitation scenarios. Each scenario can be evaluated for its long-term economic value, helping users to select the most economical alternative.

The study found that non-economic factors such pavement/tire noise, facility downtime, negative environmental impacts, and so forth may also impact the decisions for some local agencies. As a result, an optional non-economic scoring method that aims at selecting the most appropriate treatment when multiple treatments are available was developed.

The scoring method utilizes the AHP, which is used to calculate the weights of different factors based on pairwise comparisons. The tool allows up to three users to input their pairwise comparisons of the selection factors. Performance, user satisfaction, and other non-economic parameters are used in the scoring system.

The decision-aid framework and the tool developed in this project are anticipated to help local agencies (cities and counties) select the most feasible and economic pavement treatments and improve the serviceability of the Iowa pavement network. The spreadsheet tool provides a simple and easy way to select the most economic treatments.

1. INTRODUCTION

Many pavement treatment methods are available in the industry. For example, flexible pavement preservation and maintenance treatments include crack treatment, fog seal, chip seal, thin hot-mix overlay, thin cold seal, and others. Rehabilitation treatments such as mill and overlay, cold-in-place recycle, full-depth reclamation, and whitetopping are also available. Rigid pavement preservation and maintenance treatments include crack and joint sealing, under-sealing, retrofit of dowels, and others. Bonded concrete overlay, unbounded concrete overlay, and reconstruction are some examples of the rehabilitation and replacement methods for rigid pavements.

When a preservation treatment is properly applied, it is expected to economically extend the cost of the pavement by addressing the existing distresses such as cracking. In addition, it is expected to prevent future distresses that shorten a pavement's service life. However, those preservation treatments are not typically expected to strengthen the structure of a pavement. Preservation treatments need to be applied at the right time to maximize the expected benefits.

Rehabilitation treatments should be used to enhance the pavement structure and restore heavily deteriorated pavements to an acceptable condition. Three different procedural decision-making steps are typically utilized to select the most appropriate treatment method for a pavement under consideration: evaluate the existing conditions, determine technically feasible treatment options, and analyze those feasible options and select the most appropriate treatment. In evaluating the existing conditions, various structural and functional pavement condition indices are used along with other visual inspection data and climate, traffic loading conditions, etc.

With the existing condition data, technically feasible treatment alternatives are recommended. Rehabilitation or replacement treatments are considered when structural deterioration is observed. With no evidence of pavement structural deterioration, preservation treatments are typically considered. Among the feasible treatment alternatives, the most appropriate treatment is selected.

To facilitate this decision-making process, a decision tree or matrix-based method has been most commonly used by state departments of transportation (DOTs). Hicks et al. (2000) provides a set of examples of those decision tree and matrix-based methods for flexible pavements used by various state DOTs. Iowa is not an exception. For instance, Jahren et al. (2007) developed a decision matrix for flexible pavement preservation treatments using seven test sections since 1997 and other information.

There are some known limitations of using a decision tree or matrix-based method (Hicks et al 2000). One of the most noticeable concerns is that, when competing treatment alternatives are available for a pavement, it is not useful unless a well-defined method for determining the benefits or the return on investment (ROI) is available. This issue is more common when selecting a preservation treatment than when selecting a rehabilitation method because more competing options exist for preservation.

The benefits or value of various pavement treatments vary depending on the treatment type, when it is applied, and the condition of the pavement at the time of application (Peshkin et al. 2004). Also, it appears that no universal definition of the benefits from pavement preservation and rehabilitation treatments exists yet (Dawson et al. 2011). The California DOT (Caltrans) has developed and used a subjective judgment-based method in which 11 different factors are considered in evaluating the value or the effectiveness of treatment alternatives for comparison purposes (Caltrans 2003). Other publications report different quantitative and qualitative methods to calculate cost effectiveness of treatment options (Hicks et al. 2000 and Pittinger et al. 2011). A well-defined method to quantify the benefits of each treatment option will greatly facilitate the treatment selection decision.

1.1. Problem Statement

The American Society of Civil Engineers (ASCE) estimate in 2013 was that $170 billion in capital investment is needed annually to improve the nation's road infrastructure, which is graded with a poor grade of D+. Poor road conditions cost motorists $67 billion a year in repairs and operating costs, or $324 per motorist each year (ASCE 2013).

Pavement condition data for Iowa was also alarming. An estimated 45 percent of major roads in the state were in fair condition, and large truck traffic on Iowa's highways will increase about 66 percent from 2015 to 2040, which will definitely impact Iowa's highways in terms of congestion and pavement deterioration (ASCE 2015).

As the need for pavement treatments (preservation, rehabilitation, and replacement) is significantly growing, the Iowa DOT and local agencies need to enhance their pavement asset management system to develop effective and reliable short-term and long-term pavement management plans. Asset management offers management-level solutions for the optimal use of limited financial resources. Asset management goals include the abilities to analyze the full range of preservation, rehabilitation, and replacement options in the same matrix and compare available strategies against alternatives. Logical, reliable, and transparent decision-making processes from a successful asset management program will truly change the pavement service delivery framework.

Iowa DOT staff are fully aware of the short- and long-term benefits of implementing asset management by local agencies and has been charged with developing a "world-class" asset management program. The Iowa DOT's *Road Use Tax Fund Efficiency Report* from January 2012 includes the following: "The Iowa DOT will work closely with local jurisdictions to implement an asset management tool and process across all jurisdictions. Local jurisdictions have the majority of the public roadway system in Iowa; therefore, through this effort there is potential to generate significant savings at the local level." The estimated one-time savings was listed as $11 million in the report (Iowa DOT 2012).

When the pavement condition falls below a certain threshold value, various treatment options are considered and one of them is selected and applied to the pavement. During this decision-making process, local Iowa agencies need to have a defensible framework to select the most appropriate treatment for a pavement under consideration. The selected treatment option must be technically feasible, cost effective, and offer the highest return among the feasible group of treatments.

Through previous research efforts (including Jahren et al. 2007), the Iowa DOT has some matrix-based tools to identify feasible treatment options when the pavement conditions are given. However, current tools fall short of offering a method to evaluate the return value of a treatment option. This is an especially important issue when multiple treatment options become competing candidates for a specific pavement treatment project.

In addition, existing tools fail to meet local agency needs and limitations. Currently, engineering judgment and experience-based opinions are used in making final decisions.

Decision makers need a tool to evaluate which treatment option can maximize the return on their investment decision. Therefore, there was a strong need to develop a pavement asset management framework that not only identifies technically feasible solutions, but also helps asset managers to select treatment options with the highest return. This framework will greatly assist local Iowa agencies in enhancing their pavement asset management as well as help in achieving the DOT’s long-term goal of implementing a comprehensive asset management program.

1.2. Objectives

This project had five objectives to accomplish the final goal of developing a pavement asset management framework for selecting a pavement treatment through evaluating benefits of various treatment options from do nothing to full replacement:

- Develop a framework for selecting feasible treatment options when the conditions of a pavement section are given
- Develop a methodology in assessing ROI values of various treatment options available for Iowa pavements
- Develop a spreadsheet-based decision-aid tool that can be used by local agencies in selecting the most appropriate treatment option
- Conduct case studies using the tool developed in this project and validate the tool
- Train local agency engineers for rapid dissemination of the tool

1.3. Research Approach

Figure 1 shows the research approach adopted.

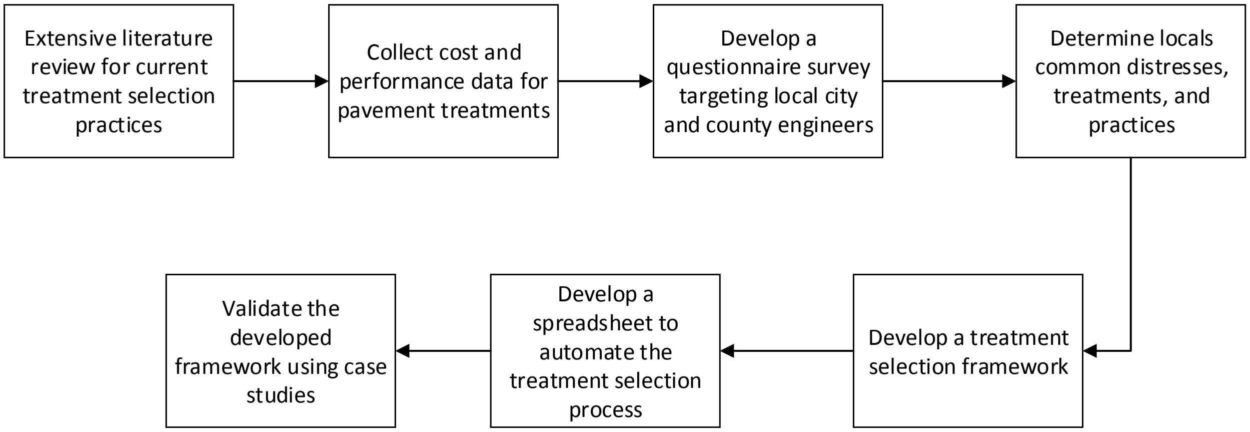

Figure 1. Research approach

The research approach involved an extensive literature review for different treatment selection decision-making frameworks used by DOTs such as the California DOT (Caltrans), the Illinois DOT (IDOT), the Minnesota DOT (MnDOT), the Nebraska Department of Roads (NDOR), and the South Dakota DOT (SDDOT). Independent studies were also included in the literature review. Practices were extensively reviewed and documented to build a customized treatment selection framework for local agencies.

In addition, performance and cost data for maintenance and rehabilitation treatments were gathered from various resources. The performance and cost database can be used as a guide for local agencies that do not collect or document data regularly.

A review of threshold values for different distresses was conducted. DOT practices and the Federal Highway Administration (FHWA) Distress Identification Manual for the Long-Term Pavement Performance Program (Miller and Billenger 2003) were used to set guiding threshold values for local agencies.

A survey questionnaire was sent out, targeting local City and County engineers. The survey aimed at identifying the common existing pavement distresses and treatments used by Iowa cities and counties. The treatment selection framework was then limited to the common existing distresses and treatments used.

The ROI definition was also defined to fit the needs of local agencies. The calculation procedure was developed based on the equivalent uniform annual cost (EUAC) for various treatments.

1.4. Report Organization

This report presents a treatment selection framework for local agencies. The remainder of the report is organized as follows. The second chapter presents an extensive literature review for treatment life expectancies, treatments cost data, DOT practices, and level of service indicators. The third chapter summarizes the results of the survey questionnaire that targeted local City and

County engineers. The fourth chapter presents the treatment selection framework for both flexible and rigid pavements. The scoring method for technically feasible treatments is also presented. The last chapter presents the conclusions and observations for the research.

2. LITERATURE REVIEW

Publications are rich in the areas of domestic and international pavement management systems, pavement treatments, decision-support models for pavements, pavement deterioration process, lifecycle cost analysis, and so forth. These documents have been reviewed and are summarized in this chapter.

Since the main goal of this literature review was to investigate potential approaches and methodologies that may be adapted and used to help meet the objectives of this project, valuable information such as treatments life expectancies, unit costs, and DOT maintenance and rehabilitation practices was gathered from sources throughout the US.

In this chapter, different types of pavement maintenance and rehabilitation treatments for flexible and rigid pavements are discussed first. Life expectancy data or service lives for each pavement treatment were collected from different studies and a discussion of the assumptions and condition associated with each treatment life expectancy reported is presented. In addition, various resources reported the unit cost for maintenance and rehabilitation treatments, and these unit costs were summarized and are presented. A discussion for state DOT maintenance and rehabilitation practices such as Illinois, Michigan, South Dakota, and Utah are then presented in this chapter. For each state agency, the decision-making framework is summarized along with the treatments, distresses, and level of service indicators used. Finally, this chapter includes a discussion on level of service indicators from the literature review.

2.1. Pavement Treatments

Mainly, there are two pavement types under investigation for this study: flexible pavement, or asphalt concrete (AC), and rigid pavement, or Portland cement concrete (PCC). Table 1 summarizes the different treatment types for the two pavement types.

Table 1. Treatment categories for flexible and rigid pavements

Asphalt Pavements		Portland Cement Concrete Pavements	
Maintenance and Preservation	**Rehabilitation**	**Maintenance and Preservation**	**Rehabilitation**
Cape Seal	NovaChip	Crack Sealing	Dowel-Bar Retrofit (DBR)
Chip Seal	Cold-Mix Asphalt Concrete	Joint Sealing	Bonded Concrete Overlay
Chip Seal over Geotextile	Hot-Mix Asphalt, structural	Diamond Grinding	Unbonded Concrete Overlay
Microsurfacing	Cold In-Place Recycling	Diamond Grooving	Hot-Mix Asphalt Overlay
Crack Filling	Hot In-Place Recycling	Slab Stabilization	Rubblization
Crack Seal	Full-Depth Reclamation	Partial-Depth Repairs	
Fog Seal	Cold Milling with Hot-Mix Asphalt Overlay	Full-Depth Repairs	
OGFC	Whitetopping, unbonded		
Otta Seal	Whitetopping, bonded		
Sand Seal			
Scrub Seal			
Slurry Seal			
Multiple Surface Treatments			
Thin Hot-Mix Asphalt Overlay			

There are many types of preservation, maintenance, and rehabilitation treatments adopted by state DOTs and described in the literature. Preventive maintenance can be defined as an action performed that should improve or extend the pavement functional life (Johnson 2000). Preventive maintenance activities should delay pavement failure and reduce the need for routine maintenance (Johnson 2000). Thus, applying a preventive maintenance treatment will provide the pavement an extended period of life expectancy. The life extension depends on the type of treatment applied. Preventive maintenance can be applied to pavements that are structurally sound. Maintenance treatments are not recommended when pavements suffer from major structural deficiencies.

In 2005, The FHWA issued a memorandum to define pavement preservation program components. Pavement preservation actions are meant to restore serviceability and extend service life; however, they should not increase strength or capacity of the pavement (FHWA 2005). A preservation program consists of preventive maintenance, minor rehabilitation, and routine maintenance (FHWA 2005). Pavement preservation should be applied when the pavement is in good condition to restore the pavement to its original condition (FHWA 2005).

Preventive maintenance is the application of cost effective treatment to structurally sound pavement to extend its service life. Crack sealing, chip sealing, microsurfacing, and diamond grinding are considered some examples of preventive maintenance (FHWA 2005).

Rehabilitation treatments can be applied to restore the existing structural capacity of a pavement by increasing the pavement thickness or strengthening the pavement section (FHWA 2005). Pavement rehabilitation can be divided into two categories: minor and major rehabilitation. Minor rehabilitation treatments are meant to eliminate age-related surface cracking in flexible pavements while major rehabilitation is considered structural enhancement that extends the service life (FHWA 2005).

Routine maintenance—such as crack filling, pothole patching, and isolated overlays—is a day-to-day activity that preserves the condition of the pavement (FHWA 2005).

The life expectancy for each treatment was reported by various studies. The minimum and maximum life expectancy for each treatment varies from one study to another. Usually, the life expectancies are associated with the factors that affect them. However, some studies and DOT guides did not report the affecting factors. These factors are as follows:

- Climate and environmental condition
- Traffic loadings
- Volume of traffic
- Quality of material
- Treatment mix design
- Pavement existing conditions
- Construction quality

The climate and environmental conditions refer to the number of freeze and thaw cycles, precipitation, and temperature. It is expected that treatment performance will be affected negatively in environments with more frequent freeze and thaw cycles.

Traffic loadings are related to the percentage of trucks using the road while volume of traffic refers to the average daily traffic.

The quality of material varies from one state to another. In addition, the quality of materials can vary within the same state.

The mix design of the treatment affects the treatment life expectancy. For example, a one inch hot-mix asphalt (HMA) overlay is not expected to perform as well as a five inch thick HMA overlay.

The pavement's existing condition prior to applying a specific treatment affects the performance of the treatment. For example, the performance of crack sealing for narrow cracks should be better than crack sealing for wide cracks assuming that all other factors remain the same.

The construction quality also affects the treatment life expectancy. High measures of quality assurance and quality control can affect the treatment performance.

Treatment lifecycle costs were reported by several studies. The cost ranges were formed by researching the most up-to-date studies and formulating a reasonable range of lifecycle costs. The average cost for each treatment is given in cost per square yard ($\$/yd^2$), cost per ton ($/ton), or other units. Variations in treatment lifecycle costs reported by various studies are expected to occur because of the following reasons:

- Date of the study
- Location of the study
- Treatment project size
- Road type
- Project conditions
- Mix design
- Specifications and material quality used for each treatment project

The timing of the study is an important factor that should be considered when examining the treatment lifecycle costs. For example, Maher et al. (2005) reported that the chip seal cost range was from $0.80 to $1.25 per square yard. The treatment lifecycle costs reported by Maher et al. (2005) were from 10 years ago. Costs variations and inflation should be considered when looking at the data reported by different studies.

The location of the study is another important factor that should be considered, as treatment costs vary from one region to another.

The project size affects the treatment lifecycle cost. Larger quantities can make material prices less expensive.

Also, in some cases, the severity of the distress can affect the cost of the treatment. For example, the extent of cracking affects the cost of crack filling/sealing (NDOR 2002).

Road type and project conditions can definitely affect treatment lifecycle costs. For example, roads with heavy traffic volumes require more traffic control and safety measures. The costs on these roads can be higher than on low-volume roads. Also, some work items might be required for some projects because of their existing conditions, such as bridge approach work or sidewalks.

Treatment mix design and overlay thickness will definitely change the treatment lifecycle costs.

Specifications and material quality also change the treatment costs in terms of number of tests required and level of quality materials required.

Most, if not all, studies did not report these factors while reporting the treatment lifecycle costs for each treatment. Agencies should use their up-to-date cost-estimating guides when estimating costs for their treatment projects.

2.2. Maintenance and Preservation Treatments for Asphalt Pavements

Crack Sealing

Crack sealing is a treatment method that is used to prevent water and debris infiltration. In addition, crack sealing is considered effective at mitigating or retarding moisture damage, crack deterioration, roughness, and rutting (IDOT 2010). Crack sealing can be used to seal 0.75-inch wide cracks (Johnson 2000 and IDOT 2010). Types of crack sealing are listed as follows (Johnson 2000):

- Clean and seal
- Saw and seal
- Rout and seal

The clean and seal method involves cleaning the crack using compressed air. Afterward, the crack is filled with sealant (Johnson 2000).

The saw and seal method involves using a pavement saw to create a transverse joint along a newly placed pavement. A sealant material is then used to fill the joints created (Johnson 2000). The saw and seal crack treating method is used to address shrinkage cracks due to thermal changes.

Finally, the rout and seal method is used to address transverse and longitudinal cracks. The method involves creating a reservoir centered over the existing cracks (Johnson 2000). The created reservoir is filled with sealant to prevent water and debris infiltration.

Excessive use of crack sealing and sealant material will lead to loss of friction and high roughness (Johnson 2000, IDOT 2010, and SDDOT 2010). The performance of crack sealing is not affected by traffic volumes or percentage of trucks (IDOT 2010 and SDDOT 2010). It is not recommended to apply crack sealing when the pavement is severely deteriorated (IDOT 2010 and SDDOT 2010).

Table 2 contains life expectancy and cost data gathered for crack sealing.

Table 2. Crack sealing life expectancy and cost data

State	Reference	Life Expectancy (yrs)	Cost	Remarks
Illinois	IDOT 2010	2-8		Not specified
Minnesota	Johnson 2000	3	\$0.10 to \$0.30/lin. ft	Type of crack seal is crack Seal-Clean and Seal; should be applied when crack width is still narrow
Minnesota	Johnson 2000	7-10	\$1.70/lin. ft	Type of crack seal is crack Seal-Saw and Seal; extended service life ranges from 7 to 10 years if applied on a new asphalt pavement (48 hours after pavement)
Minnesota	Johnson 2000	3	\$0.50 to \$0.85/lin. ft	Type of crack seal is crack Seal-Rout and Seal; should not be applied if cracks are too wide
Nebraska	NDOR 2002	3-5	\$0.55 to \$0.60/lin. ft^2	Not specified
Ohio	ODOT 2001	2-3	–	Not specified
Pennsylvania	Morian 2011	2-10	–	Average expected life is 4.4 years
South Dakota	SDDOT 2010	2-4	–	Crack treating method is used with low quality materials and minimal crack preparation
South Dakota	SDDOT 2010	2-8	–	Rout and seal cracks method is used with high quality materials and significant crack preparation work
–	Hicks et al. 2000	2-5	\$0.50/yd^2	Life expectancy is based on traffic and environmental conditions

Life expectancy and costs depended on the type of crack sealing method used. The minimum life expectancy reported was 2 years while the maximum was 10 years.

Crack Filling

Crack filling is defined as the process of placing a bituminous filler material into cracks to reduce water infiltration (IDOT 2010). Crack filling can be used to address cracks with widths up to 1 inch. Crack preparation is minimal—debris is blown from the cracks using compressed air before the filling process (Johnson 2000).

It is not recommended to apply crack filling on heavily deteriorated pavements (IDOT 2010). The performance of crack filling is not affected by traffic volumes or percentage of trucks (IDOT

2010). However, crack filling may have a negative impact on pavement roughness and friction (IDOT 2010).

The life expectancy of crack filling is typically short. IDOT (2010) reported that crack filling had a 2- to 4-year life expectancy and Johnson (2000) reported different life expectancies for crack filling based on the filler material used. Life expectancies for crack filling in Minnesota from Johnson (2000) were as follows:

- Asphalt emulsions (a few months to up to 1 year)
- Rubberized fillers (2 to 3 years)
- Microsurfacing material (2 to 3 years)

Slurry Seal

Slurry seal is a cold-mix surface treatment that contains a mixture of emulsified asphalt, dense-graded crushed fine aggregate, mineral filler, and water. It is considered a preventive maintenance technique for asphalt pavements. Slurry seal is applied at the thickness of the largest aggregate in the mix (Maher et al. 2005).

Slurry seal is used to seal minor cracks, correct small surface irregularities, halt raveling, and improve ride quality and friction properties slightly (Maher et al. 2005 and Hicks et al. 2000). This type of treatment is supposed to fill fine cracks in the pavement surface. In addition, slurry seal should fill mild imperfections and restore uniform color and texture (NDOR 2002). The rate of surface oxidation is slowed down, and water infiltration is prevented by applying slurry seal to the pavement surface (NDOR 2002).

There are some limitations and cautions reported by some DOTs when considering slurry seal as a surface treatment. NDOR (2002) recommends that slurry seal should not be applied if the wheelpath depression is greater than 0.5 inches. In addition, slurry seal should not be applied when structural deficiencies are existing (IDOT 2010). Maher et al. (2005) stated that slurry seal should not be applied for roadway gradients steeper than 8 percent. In terms of weather restrictions, slurry seal should not be placed if it is raining/freezing or there is a risk of raining/freezing. The minimum air temperature for slurry seal application is 50 ºF (Maher et al. 2005).

Slurry seal does not have potential long-term environmental impacts. In addition, slurry can be recycled with the underlying asphalt. The tire/road noise for slurry seal is low to moderate 72 to 79.5 dB(A) at a distance of 25 feet (Maher et al. 2005).

Table 3 summarizes the life expectancy and cost data for slurry seal reported by different studies and DOTs.

Table 3. Life expectancy for slurry seal

State	Reference	Life Expectancy (yrs)	Cost	Remarks
Illinois	IDOT 2010	3-6	–	Not specified
Minnesota	Johnson 2000	3-5	$1.50/yd^2$	Traffic loading, environmental conditions, existing pavement condition, material quality, mix design, and construction quality are factors that affect the life expectancy
Nebraska	NDOR 2002	3-8	$45,000/two-lane mile	Not specified
–	Hicks et al. 2000	3-7	$0.90/yd^2$	Treatment life expectancy is based on traffic and environmental conditions
–	Maher et al. 2005	3-8 (avg. 5)	$0.75-$1.50/yd^2$	Mix types, traffic volumes, and environmental conditions affect life expectancy
–	Bolander 2005	5-10	–	ADT is less than 100
–	Bolander 2005	5-8	–	ADT is greater than 100 and less than 500
–	Li et al. 2006	–	$1.60/yd^2$	Not specified

The life expectancy of slurry seal varied according to traffic volumes, traffic loading environmental conditions, construction quality, existing pavement condition, and other factors. The minimum expected life reported was 3 years while the maximum reported was 10 years. The cost data varied according to the study. Slurry seal costs can vary according to the study date, location, project size, project conditions, and so forth.

Microsurfacing

Microsurfacing consists of a mixture of polymer-modified asphalt emulsion, mineral aggregate mineral filler, water, and other additives. The components are properly proportioned, mixed, and spread on a paved surface (Maher et al. 2005, NDOR 2002, and Hicks et al 2000). Microsurfacing can be placed with a thickness up to three times the size of the largest aggregate. Microsurfacing is best suited to address rutting, raveling, oxidation, bleeding, and loss of surface friction (Maher et al. 2005). Additionally, this treatment is suitable for use on high traffic volume roads (NDOR 2002). Microsurfacing allows the traffic to be restored within one hour after application (Lee and Shields 2010). NDOR (2002) stated that microsurfacing is capable of filling wheel ruts up to 1.5 inch deep.

It is worth mentioning that microsurfacing does not address any structural deficiencies (Maher et al. 2005). IDOT (2005) does not recommend applying microsurfacing when the pavement contains structural failure, severe thermal cracking, or pavement deterioration. In terms of weather restrictions, microsurfacing is similar to slurry seal and should not be applied when there is a risk of rain or freezing. The minimum air temperature for placing microsurfacing is 50 ºF.

There are no potential long-term environmental impacts for microsurfacing. In addition, microsurfacing can be recycled as an unbonded or stabilized material (Maher et al. 2005). The tire/road noise for microsurfacing is similar to slurry seal at 72 to 79.5 dB(A) at a distance of 25 feet (Maher et al. 2005).

Table 4 contains the life expectancy and cost data for microsurfacing as reported by different studies and DOTs.

Table 4. Microsurfacing life expectancy and cost data

State	Reference	Life Expectancy (yrs)	Cost	Remarks
Arizona	Li et al. 2006	–	$3.50/yd^2	Not specified
California	Caltrans 2009	5-7	–	Affected by workmanship, current condition pavement, and traffic level
Illinois	IDOT 2010	4-7	–	Not specified
Indiana	Labi et al. 2006	4-6	–	Service life is approximately 5 years if IRI is used as a performance indicator
Indiana	Labi et al. 2006	7-8	–	Average service life is 7 years if PCR is used as a performance indicator
Indiana	Labi et al. 2006	22-27	–	Average service life can reach 24 years if rut depth is used as a performance indicator; extended service life for non-Interstate roads are higher than extended service life for Interstate roads
Nebraska	NDOR 2002	3-8	$41,000-$43,000/ two-lane mile	Not specified
Ohio	ODOT 2001	5-8	–	Existing condition prior to applying microsurfacing affects expected service life of the treatment
Minnesota	Johnson 2000	7	$1.50-$2.00/yd^2	Life expectancy of 7 years or more for high traffic; life expectancy can go considerably higher for low to moderate traffic; in addition, service life depends on pavement existing condition at treatment application
South Dakota	SDDOT 2010	4-7	–	Not specified
–	Hicks et al. 2000	3-9	$1.25/yd^2	Treatment life expectancy is based on traffic and environmental conditions
–	Maher et al. 2005	5-8 (avg. 7)	$2.60-$3.30/yd^2	Mix types, traffic volumes, and environmental conditions affect life expectancy
–	Peshkin et al. 2004	4-7	–	Extended service life is between 4 to 7 years only if microsurfacing was applied in a preventive maintenance mode

The minimum expected service life for microsurfacing was 3 years while the maximum reported was 27 years. Labi et al. (2006) used different performance indicators to report the life expectancy of microsurfacing. The life expectancy of microsurfacing varied according to the performance indicator used (Labi et al. 2006).

Chip Seal

A chip seal is developed by spraying a bituminous binding agent and spreading a thin aggregate cover. Chip seals can be used to improve the surface texture and improve friction properties (NDOR 2002 and SDDOT 2010). Also, chip seals provide some benefits to distresses such as transverse and longitudinal cracking, raveling, weathering, and moisture infiltration (IDOT 2010). However, a chip seal is not an alternative to crack sealing, and all cracks should be sealed before applying the chip seal. Chip seals can be applied to low- or high-volume roads and highways. However, the use of non-crushed aggregate should be restricted to high-volume roads (NDOR 2002). Chip seals can be applied over a geotextile layer to reduce reflection cracks. The integration of the geotextile reinforcement can provide sufficient subbase integrity. Chip seals can be applied to form two or three layers, extending the service life of the surface (Maher et al. 2005 and IDOT 2010).

A chip seal treatment is not recommended when the pavement shows wide cracks, many potholes, high roughness, or severe deterioration (IDOT 2010). Chip seals should not be applied to roads with gradients steeper than 8 percent (Maher et al. 2005). Also, chip seals are prone to damage by plowing in snow plowing areas. Chip seals should not be applied when there is a risk of freezing temperatures.

In terms of short-term environmental impacts, significant heat is produced during the asphalt cement placement process. This significant heat can have an impact on nearby vegetation. Also, the use of cutback asphalts results in hydrocarbon emissions (Maher et al. 2005).

Chip seal material can be recycled and reused as unbound or stabilized material. The noise level is similar to microsurfacing and slurry seal. The tire/road noise for chip seal is 72 to 79.5 dB(A) at a distance of 25 feet (Maher et al. 2005).

Table 5 contains chip seal life expectancy and cost data as reported by several studies and DOTs.

Table 5. Chip seal life expectancy and cost data

State	Reference	Life Expectancy (yrs)	Cost	Remarks
Arizona	Li et al. 2006	–	$1.78/yd^2$	Not specified
Illinois	IDOT 2010	4-6	–	Not specified
Minnesota	Johnson 2000	3-6	$0.40-$0.70/yd^2$	Life expectancy reported for single seals; life expectancy for double seals not reported; however, it depends on the type and amount of traffic
Nebraska	NDOR 2002	3-6	$8,000-$9,000/two-lane mile	Not specified
Ohio	ODOT 2001	5-7	–	Existing condition of pavement affects chip seal service life
South Dakota	SDDOT 2010	6-8	–	Single seal
–	Hicks et al. 2000	3-7	$0.85/yd^2$	Based on author experience, traffic, and environmental conditions
–	Maher et al. 2005	3-7	$0.80-$1.25/yd^2$	Life expectancy depends on construction materials, environmental conditions, and traffic volumes; chip seals placed over paved roads has a higher life expectancy compared to chip seals placed over stabilized aggregate
–	Morian 2011	4-7	–	Not specified
–	Raza 1992	4-7	–	Chip seals have been applied to pavements with traffic volume greater than 5,000 vehicles per day

The minimum life expectancy reported for chip seals was 3 years while the maximum life expectancy reported was 8 years.

Cape Seal

Cape seal is a thin treatment that consists of slurry seal or microsurfacing that is applied to a recent chip seal. The main purpose of the slurry is to fill the voids in the chip seal and prevent chip loss. Cape seals can provide a durable roadway with high skid resistance (Maher et al. 2005). Also, cape seals are applied to address longitudinal, transverse, and block cracking. In addition, the treatment can address friction loss, raveling, and minor roughness (IDOT 2010).

Cape seals are less prone to damage from snow plowing than chip or slurry seal (Maher et al. 2005).

The treatment is not recommended when the pavement suffers from wide cracks, many potholes, high roughness, or severe deterioration (IDOT 2010). Cape seals are not widely used in the US (Maher et al. 2005). As a result, information about design and construction is limited according to the region. The weather limitation of cape seal is the same as microsurfacing, chip seal, and slurry seal. Cape seals should not be applied if there is a risk of rain or freezing weather. Cape seals are not recommended if the road gradient is steeper than 12 percent.

Heat produced with cape seal construction is reduced when emulsified asphalt is used. The tire/road noise is similar to microsurfacing, slurry seal, and chip seal. However, the tire/road noise for cape seal is lower than chip seal (Maher et al. 2005).

Table 6 summarizes cape seal life expectancy and cost data reported from several studies.

Table 6. Cape seal life expectancy and cost data

State	Reference	Life Expectancy (yrs)	Cost	Remarks
Illinois	IDOT 2010	4-7	–	Not specified
–	Maher et al. 2005	7-15 (avg. of 9)	\$2.25-\$3.00/yd^2	Life expectancy is affected by mix type, traffic volume, and degree of routine maintenance
–	Bolander 2005	8-15	–	ADT less than 100
–	Bolander 2005	6-8	–	ADT greater than 100 and less than 500

The minimum expected life reported was 4 years while the maximum reported was 15 years. Maher et al. (2005) reported that the unit cost of cape seal was from \$2.25 to \$3.00 per square yard. Other studies did not report the cost of cape seals.

Fog Seal

Fog seal involves a light application of slow setting emulsified asphalt diluted with water (NDOR 2002). Fog seal is considered appropriate for porous surfaces.

One of the limitations of fog seal application is that it cannot be applied on low skid resistance surfaces (Maher et al. 2005). In addition, fog seal is not recommended for high-volume roadways because it reduces the skid resistance. Similar to other preservation and maintenance treatments, fog seal should not be applied if there is a risk of rain or freezing weather (Maher et al. 2005). The spraying process of fog seal can have an impact on nearby vegetation (Maher et al. 2005).

Table 7 summarizes the life expectancy and cost data of fog seals from several studies.

Table 7. Fog seal life expectancy and cost data

Reference	Life Expectancy (yrs)	Cost	Remarks
Hicks et al. 2000	1-4	$0.45/yd^2$	Expected life varies according to traffic and environmental conditions
Maher et al. 2005	1-3	$0.20-$0.50/yd^2$	Service life depends on construction materials, environmental conditions, and traffic volumes
Morian 2011	1-3	–	None
Bolander 2005	2-4	–	ADT less than 100
Bolander 2005	1-3	–	ADT greater than 100 and less than 500
Peshkin et al. 2004	1-2	–	Treatment should be applied in a preventive maintenance mode
IDOT 2010	1-3	–	Not specified
NDOR 2002	1-4	–	Not specified
SDDOT 2010	1-3	–	Not specified
Johnson 2000	1-2	$0.10-$0.20/yd^2$	Expected service life depends on underlying pavement and exposure to sunlight
Li et al. 2006	–	$1.28-$1.38/yd^2$	Not specified

Fog seals have a short life expectancy compared to other surface treatments. The minimum service life reported was 1 year while the maximum was 4 years. Also, the cost data indicated that fog seals were relatively less expensive than other surface treatments.

Open-Graded Friction Course (OGFC)

An open-graded friction course (OGFC) is a porous HMA concrete wearing course. An OGFC contains little sand or dust with high air voids content. The main function of the air voids is to drain water. An OGFC has good frictional properties and reduces hydroplaning. In addition, an OGFC reduces road noise and headlight glare (Maher et al. 2005). However, an OGFC does not improve major structural failure.

It is not appropriate to apply OGFCs to areas that water, oil, snow, or other liquids may gather (Caltrans 2006). Also, OGFCs are not recommended for roads with significant heavy traffic

(Maher et al. 2005). The use of OGFCs in cold climates is limited since they require special winter maintenance procedures (Maher et al. 2005).

The life expectancy and cost of OGFCs were not reported by many studies like other treatments. Maher et al. (2005) reported that the life expectancy of an OGFC was from 8 to 12 years and the cost was from $9.20 to $11.20 per square yard.

Sand Seal

Sand seal is a thin asphalt surface treatment that is similar to the chip seal treatment. The main difference between sand seal and chip seal is that a finer aggregate is used in the application process of a sand seal (Maher et al. 2005). Sand seal is used to address distresses such as cracking, raveling, bleeding, and surface wear (Maher et al. 2005). The application of sand seal should be limited to roads with low traffic volume (IDOT 2010). Sand seal can improve poor friction and reduce moisture damage, cracking, raveling, roughness, and rutting (IDOT 2010).

The treatment is not recommended when structural failure exists (IDOT 2010 and Maher et al. 2005). Also, sand seal application is not recommended on old pavements with little life remaining (IDOT 2010). Sand seal should not be applied to roads with gradients steeper than 8 percent. In addition, sand seal is prone to damage in snow plowing areas (Maher et al. 2005).

Table 8 summarizes the life expectancy and cost data of sand seal.

Table 8. Sand seal life expectancy and cost data

Reference	Life Expectancy (yrs)	Cost	Remarks
Maher et al. 2005	2-6 (avg. 3)	$0.50-$1.25/yd^2	Construction materials used, environmental conditions, and traffic volumes affect life expectancy
Bolander 2005	2-4	NR	ADT less than 100
Bolander 2005	1-5	NR	ADT greater than 100 and less than 500
IDOT 2010	3-4	NR	None
SDDOT 2010	6-8	NR	None

The minimum expected service life reported was 1 year while the maximum was 8 years. Maher et al. (2005) reported that the cost of sand seal was from $0.50 to $1.25 per square yard.

Scrub Seal

Scrub seal is a thin asphalt surface treatment that is applied by spraying emulsified asphalt onto an existing pavement. A broom is dragged across the surface to scrub the emulsified asphalt into the surface cracks. Scrub seal is used to address distresses such as small cracks, raveling, bleeding, wear by tire abrasions, and loss of surface friction (Maher et al. 2005). Non-working cracks can be treated using a crack filling treatment method by the placement of materials into the non-working cracks to reinforce the pavement. On the other hand, working cracks can be treated using a crack sealing treatment method by the placement of materials into working cracks (Hicks et al. 2000). Scrub seal can be applied to low- and high-volume roads (Maher et al. 2005).

Similar to other maintenance and preservation treatments, scrub seal is not recommended for roads with gradients steeper than 8 percent. Also, scrub seal, is subject to damage due to snow plow activities (Maher et al. 2005). Scrub seal should not be applied if there is a risk of rain or freezing (Maher et al. 2005).

Table 9 summarizes scrub seal life expectancy and cost data reported by several resources.

Table 9. Scrub seal life expectancy and cost data

Reference	Life Expectancy (yrs)	Cost	Remarks
Maher et al. 2005	2-6 (avg. 3)	\$0.50-\$1.30/yd^2	Construction materials used, environmental conditions, and traffic volumes affect life expectancy
NDOR 2002	2-5	NR	None
SDDOT 2010	5-7	NR	None

The minimum expected service life was 2 years while the maximum was 7 years. Maher et al. (2005) reported that the cost of scrub seal was from \$0.50 to \$1.30 per square yard.

Thin Hot-Mix Asphalt (HMA) Overlay

Thin HMA overlays are defined as a blend of aggregate and asphalt cement (Johnson 2000). The three types of thin HMA overlays are dense-graded, open-graded friction course, and gap-graded. The use of thin HMA overlay is intended to improve the functional performance of the pavement (Johnson 2000).

Applying a thin HMA overlay should improve ride quality and skid resistance. Thin HMA overlays can increase the structural capacity of the pavement; however, they should not be applied when there are structural failures in the pavement (SDDOT 2010).

The treatment is not affected by different traffic volumes or percentage of trucks (SDDOT 2010). SDDOT (2010) recommends repairing localized distressed areas before overlaying. Thin HMA overlays are used to address distresses such as low-severity cracking, raveling/weathering, friction loss, and high roughness (SDDOT 2010).

Table 10 summarizes the life expectancy and cost for thin HMA overlays from different resources.

Table 10. Thin hot-mix overlay life expectancy and cost data

State	Reference	Life Expectancy (yrs)	Cost	Remarks
Minnesota	Johnson 2000	5-8	\$18-\$30/ton	Not specified
Nebraska	NDOR 2002	5-8	\$45,000-\$55,000/ two-lane mile (1 in.)	Not specified
Ohio	ODOT 2001	8-12	–	Expected service life depends on overlay thickness
South Dakota	SDDOT 2010	10-15	–	Depends on overlay thickness
–	Hicks et al. 2000	2-12	\$1.75/yd^2	Life expectancy is based on traffic and environmental conditions
–	Peshkin et al. 2004	7-10	–	Treatment should be applied in a preventive maintenance mode

The minimum expected life was 2 years while the maximum was 12 years. Cost of the overlays depends on the thickness. In addition, cost of thin HMA overlay varies according to project size and location.

Patching

Different techniques of patching were found in the literature. However, patching is also considered a pavement distress (IDOT 2010 and MnDOT 2012b). Therefore, patching should be considered as a last treatment option if no other feasible treatments are available.

Spray injection patching is a patching method used by NDOR (2002). This method is considered a safe and quick method. In addition, it is capable of addressing alligator cracking, transverse cracking, edge cracks, depressions, rutting, and potholes. Spray injection patching involves mixing aggregate and asphalt binder under pressure through the machine's spray hose. The mixture is sprayed on the desired spot and covered with a layer of aggregate.

Machine patching using cold-mix asphalt is another patching method used by NDOR (2002). Machine patching using cold-mix asphalt can be used to address distresses such weathering, raveling, longitudinal cracks, alligator cracking, bleeding, rutting, and depressions.

Patching also can be done using HMA (NDOR 2002). HMA concrete patches or surface patching can be used to address ruts, corrugations, depressions, or raveling. The depth of surface patching varies between 1 and 4 inches.

2.3. Rehabilitation Treatments for Asphalt Pavements

Hot-Mix Asphalt (HMA) Overlay

HMA is a blend of coarse and fine aggregate and mineral filler with asphalt cement. The mineral filler with asphalt cement works as binder material (Maher et al. 2005). HMA is overlaid after being mixed at a plant. HMA overlays are widely used for surfacing roads in the US (Maher et al. 2005). In addition, HMA overlays can restore pavement friction and roughness and are used to repair fatigued pavements and potholes (Johnson 2000). However, thin overlays (0.75 to 1.5 inches) are not recommended when structural failure exists, such as fatigue cracking (SDDOT 2010). Milling should be combined with thin overlays when the pavement is heavily deteriorated (Johnson 2000).

Overlays are suitable for very low to high traffic ranges (Maher et al. 2005). Periodic crack sealing is required to extend the service life of overlays (Maher et al. 2005). However, other distresses can occur during the service life of an HMA overlay. In this case, a technically feasible treatment should be applied to extend the service life of the overlay. Tire/road noise is from 66.5 to 77.5 dB(A) inside a car at 50 mph while tire/road noise is from 72 to 79.5 dB(A) at a distance 25 feet from the vehicle (Maher et al. 2005).

Maher et al. (2005) reported that a structural HMA overlay had a life expectancy ranging from 15 to 20 years, depending on the mix type, environmental conditions, and traffic volumes. NDOR (2002) reported that a 5-inch thick HMA overlay had a life expectancy ranging from 8 to 15 years. The cost of thick HMA overlays was from $30 to $40 per ton (Maher et al. 2005).

Table 11 shows the agency costs for HMA overlays for National Highway Systems (NHS) and Non-National Highway Systems (NNHS) reported by Ahmed (2012).

Table 11. Agency costs for HMA overlays for different road types

Treatment Type	Unit Cost ($/Lane-Mile) - 2010 Equivalent $				Sample Size
	Mean	**Minimum**	**Maximum**	**Std. Dev.**	
Structural HMA Overlay (NHS)	$179,513	$38,096	$537,124	$156,287	21
Structural HMA Overlay (NNHS)	$207,831	$30,451	$448,338	$151,771	7

Source: Ahmed 2012

The data originated from Indiana DOT (INDOT) databases and was calculated into unit costs ($ per lane-mile) (Ahmed 2012). The INDOT databases included the following data: contract ID, total agency cost, date and year of construction, fiscal year of contract, length (in miles), number of lanes, surface type, functional class, etc. for all projects undertaken during 2001-2006 (Ahmed 2012). In addition, all of the costs were brought to the 2010 equivalent cost (Ahmed 2012). Note that the cost varied according to the road system.

Portland Cement Concrete (PCC) Overlay (Whitetopping)

Whitetopping is a rehabilitation treatment that encompasses the placement of a PCC overlay or inlay on top of an asphalt pavement (Maher et al. 2005). This treatment involves the placement of a PCC layer over a distressed HMA pavement (IDOT 2010).

The distressed HMA pavement should be milled before overlaying the PCC layer. The purpose of the milling process is to correct surface irregularities and provide a surface for bonding the overlay (IDOT 2010). Cracking, faulting, popouts, and spalling are the main distresses addressed by whitetopping (Maher et al. 2005).

Whitetopping has three different types: conventional, thin, and ultrathin (Maher et al. 2005). Conventional whitetopping is a PCC overlay or inlay 8 inches thick. Conventional whitetopping is not bonded with the AC pavement surface layer. Thin and ultrathin whitetopping rely on the bond between the PCC overlay and the AC pavement surface, which reduces the overlay thickness. The thickness for thin whitetopping can vary from 4 to 8 inches while the thickness for ultrathin whitetopping can be from 2 to 4 inches (Maher et al. 2005).

Whitetopping is a suitable treatment for low- and high-volume roads. Whitetopping provides a good ride quality after placement (Maher et al. 2005). Noise levels are considered higher than AC pavements; however, it can be reduced by using surface texturing (Maher et al. 2005).

Table 12 summarizes the life expectancy and cost data as reported by Maher et al. (2005).

Table 12. Whitetopping life expectancy and cost data

Reference	Life Expectancy (yrs)	Cost	Remarks
Maher et al. 2005	20-30	$36.00/yd^2$	Life expectancy depends on construction materials used, original asphalt pavement, environmental conditions, and traffic volumes; conventional whitetopping life expectancy is from 20 to 30 years; overlay thickness is 8 inches
Maher et al. 2005	NR	$20.00-$27.00/yd^2$	Overlay thickness is from 5 to 7 inches
Maher et al. 2005	5-15	$13.00-$16.00/yd^2$	For ultra-thin whitetopping, service life is from 5 to 15 years; overlay thickness is 2 inches

Source: Maher et al. 2005

The cost and life expectancy of whitetopping depended on the thickness of the overlay. Cost and life expectancy were typically high for conventional whitetopping (8 inches). The minimum life expectancy reported was 5 years while the maximum reported was 30 years.

Cold Milling

Cold milling is a process in which the pavement surface is removed. Specialized equipment is used to grind up the pavement to the desired depth (Maher et al. 2005). There are several reasons to utilize cold milling: remove rutting or surface irregularities, restore pavement cross slopes, and profile and restore pavement friction (Hicks et al 2000). Milling can be combined with chip seals to address moderate and severe rutting (NDOR 2002). In addition, milling can be used as a standalone treatment to address distresses such as distortion and excess asphalt (NDOR 2000). Cold milling is considered suitable for low and high road volumes (SDDOT 2010).

When using cold milling as a standalone treatment, the pavement must be structurally sound with at least a 3-inch AC layer remaining after milling (SDDOT 2010). Cold milling is not expected to extend the pavement service life (SDDOT 2010). However, NDOR (2002) reported that 1 inch of milling can extend the service life from 1 to 4 years.

Usually, cold milling is used to restore the pavement surface and prepare the pavement to receive an overlay. However, this treatment does not add structural benefit to the pavement (SDDOT 2010).

The cost of 1 inch milling was estimated to be from $7,500 to $8,500 (NDOR 2002).

Cold In-Place Recycling (CIR)

Cold in-place recycling (CIR) is a rehabilitation technique that is used to reclaim/pulverize bituminous pavement without heat to be mixed with a new binder (Maher et al. 2005). The treatment involves the use of cold milling as a method to reclaim the pavement surface. The resultant blend is used as a base for a following overlay (Hicks et al. 2000 and Maher et al. 2005).

Treatment depth is from 2 to 4 inches; however, depths can reach 5 or 6 inches in some cases (Maher et al. 2005 and IDOT 2010). The depth of the treatment depends on the depth of the distressed layer. It is essential to remove distresses and irregularities to full depth to achieve maximum benefit from the treatment.

CIR can be used for very low to medium traffic volume roads (Maher et al. 2005). For high-volume roads, thick HMA overlay is more suitable (Maher et al. 2005). CIR is a suitable treatment to address cracking, high roughness, poor friction, rutting, corrugation, and bleeding (IDOT 2010). CIR should not be used to address structural deficiencies such as severe alligator cracking (Maher et al. 2005 and IDOT 2010). The noise level of CIR surfaces is similar to HMA surfaces (Maher et al. 2005).

Table 13 summarizes the life expectancy and cost data for CIR as reported by different resources.

Table 13. Cold in-place recycling life expectancy and cost data

Reference	**Life Expectancy (yrs)**	**Cost**	**Remarks**
Maher et al. 2005	6-8	\$3.50-\$4.00/yd^2	Treatment life expectancy can be extended to 12 to 20 years if recycled hot-asphalt concrete pavement was overlaid
IDOT 2010	5-13	NR	None
NDOR 2002	8-12	NR	None

The minimum life expectancy reported was 5 years while the maximum reported was 13 years. The cost of CIR was from $3.50 to $4.00 per square yard (Maher et al. 2005).

NovaChip

NovaChip is the trade name of an ultrathin friction course. NovaChip is a paving process that involves thin layer placement of HMA over a Novabond membrane. NovaChip is capable of producing a durable surface with better skid resistance (Russell et al. 2008).

The treatment can be used for very low- to high-volume roads (Maher et al. 2005). However, the treatment has not been reported to be used by neighboring states such as Minnesota, Nebraska, and South Dakota.

The life expectancy of NovaChip was from 10 to 12 years (Maher et al. 2005). However, IDOT (2010) reported that NovaChip had a minimum life expectancy of 7 years (and a maximum of 12 years). The cost of NovaChip was from $3.50 to $6.70 per square yard (Maher et al. 2005).

Cold-Mix Asphalt Concrete (CMAC)

Cold-mix asphalt concrete (CMAC) is a blend of aggregate with emulsified or cutback asphalt. Thin CMAC overlays are used to address alligator cracking, raveling/weathering, distortion, and block cracking (NDOR 2002).

The mix does not require heating during the production process. In addition, it can be placed directly after mixing (Maher et al. 2005). The heat reduction in the mixing process results in an emissions reduction and lowers negative environmental impacts.

CMAC is suitable for very low to high traffic volume roads (Maher et al. 2005). However, it is not recommended when heavy traffic loadings exist. The tire/road noise levels for CMAC are typically similar to tire/road noise of HMA surfaces (Maher et al. 2005).

Table 14 summarizes the life expectancy and cost data for cold-mix asphalt as reported by two different resources.

Table 14. Cold-mix asphalt life expectancy and cost data

Reference	**Life Expectancy (yrs)**	**Cost**	**Remarks**
Maher et al. 2005	15-20	$30-$40/ton	Depends on mix type, environmental conditions, and traffic volumes
Johnson 2000	1	$55/ton	None

There was a significant difference between the life expectancy reported by Maher et al. (2005) and that reported by Johnson (2000).

Hot In-Place Recycling (HIR)

Hot in-place recycling (HIR) is a rehabilitation treatment that uses heat to soften the asphalt surface. After the heating process, the asphalt surface is mechanically removed (Hicks et al. 2000 and Maher et al. 2005). The recycled asphalt is blended with recycling agents and other materials to produce a recycled asphalt blend. The resultant blend is used to replace the material back on the pavement surface (Hicks et al. 2000 and Maher et al. 2005). The typical depth of this treatment is from 0.75 to 2 inches (Maher et al. 2005).

HIR is suitable for very low to high traffic volume roads (Maher et al. 2005 and IDOT 2010). IDOT (2010) has been using HIR to address distresses in the top 1 to 2 inches, such as rutting, corrugation, raveling, flushing, loss of friction, and thermal cracking.

Table 15 summarizes the life expectancy and cost data for HIR as reported by different studies.

Table 15. Hot in-place recycling life expectancy and cost data

State	Reference	Life Expectancy (yrs)	Cost	Remarks
Illinois	IDOT 2010	6-15	NR	Depends on method of HIR
Nebraska	NDOR 2002	3-6	\$22,000-\$25,000/ two-lane mile	None
–	Maher et al. 2005	2-4	\$0.75-\$3.25/yd^2	If heat-scarification with no subsequent treatment used
–	Maher et al. 2005	6-10		If heat-scarification with surface treatment used
–	Maher et al. 2005	7-14		Material remixing utilized
–	Maher et al. 2005	6-15		Material remixing and subsequent HMA overlay

The minimum life expectancy was 2 years while the maximum was 15 years. Life expectancy depended on the method of HIR. In addition, the use of surface treatment in conjunction with HIR extended the life expectancy of HIR.

2.4. Maintenance and Preservation Treatments for PCC Pavements

Crack Sealing

Crack sealing is a treatment used to prepare and place high quality materials into cracks. Sealed cracks should reduce moisture infiltration and slow the crack deterioration process (IDOT 2010). The treatment is used to address low or medium transverse or longitudinal cracking. However, this treatment should not be applied to pavements that show significant distress(es) such as faulting or spalling (IDOT 2010 and SDDOT 2010).

The performance of the treatment is not affected by the traffic volume or percentage of trucks (SDDOT 2010). However, crack sealing may result in poor ride quality and poor skid resistance (IDOT 2010 and SDDOT 2010).

Table 16 summarizes the life expectancy and cost data for crack sealing as reported by several DOTs.

Table 16. Crack sealing life expectancy and cost data

Reference	Life Expectancy (yrs)	Cost	Remarks
NDOR 2002	4-7	\$1.00-\$1.75/ lin. ft^2	Costs for crack sealing and joint sealing are the same
SDDOT 2010	4-8	NR	None
IDOT 2010	4-8	NR	None

The life expectancy of crack sealing was typically from 4 to 8 years.

Diamond Grinding and Grooving

Diamond grinding has become a major element of PCC pavement preservation projects (IDOT 2010). Diamond grinding is defined as the process of removing a thin layer, up to 0.25 inch, of concrete from the PCC surface using special equipment that has diamond saws (IDOT 2010). Diamond grinding addresses distresses such as joint faulting (Smith 2005). It can be used to remove transverse joint and crack faulting, wheel path rutting, and slab warping (Li et al. 2012). Grinding is applied when ruts in the wheel path exceed 0.5 inch (Li et al. 2012).

The application of diamond grinding leads to an increase of the surface friction and reduced pavement noise (Smith 2005). Surface grinding is considered a rehabilitation treatment for PCC pavement that can extend pavement life for 10 to 20 years. The Washington State DOT (WSDOT) has been applying surface grinding because of the effect of studded tires.

Diamond grinding is not recommended if the pavement has significant slab cracking or serviceability distresses such as D-cracking (Smith 2005). It is not recommended when the PCC pavement has significant roughness or significant faulting (Smith et al. 2008). However, IDOT (2010) has been using diamond grinding to address low- to moderate-severity faulting. Diamond grinding should be used in conjunction with load transfer restoration to address high-severity faulting (IDOT 2010 and SDDOT 2010).

Diamond grooving involves the process of cutting discrete grooves, longitudinal or transverse, in the PCC surface (IDOT 2010). The purpose of diamond grooving is to reduce hydroplaning and wet-pavement crashes (IDOT 2010). The minimum expected life for diamond grinding was 8 years while the maximum was 15 years.Table 17 summarizes the life expectancy and cost data for diamond grinding and diamond grooving.

Table 17. Diamond grinding and grooving life expectancy and cost data

State	Treatment	Reference	Life Expectancy (yrs)	Cost	Remarks
Illinois	Diamond Grinding	IDOT 2010	8-15	–	Not specified
Nebraska		NDOR 2002	12-15	$38,700-$115,400/ lane mile	Upper limit includes cost for dowel-bar retrofit
South Dakota		SDDOT 2010	8-15	–	Not specified
South Dakota	Diamond Grooving	SDDOT 2010	10-15	–	SDDOT expects a life expectancy of 10 to 15 years.

Partial-Depth Repairs

Partial-depth repairs are used to address joint spalling. The treatment involves removing small shallow areas of the deteriorated pavement. The removed areas are replaced by a repair material to restore structural integrity and ride quality (IDOT 2010). According to IDOT (2010), partial-depth repairs are not suitable for pavements with the following:

- Cracking and joint spalling caused by compressive stress
- Spalling caused by dowel-bar misalignment
- Cracking caused by improper joint construction
- Working cracks caused by shrinkage or fatigue
- Spalls caused by D-cracking

Partial-depth repairs are an alternative to full-depth repairs in areas where slab deterioration is located mainly in the upper one-third of the slab, and where the existing load transfer devices are still intact (Smith 2005 and IDOT 2010). In addition, the repairs are commonly conducted in conjunction with other concrete restoration activities, such as full-depth repairs, diamond grinding, and load transfer restoration (Smith 2005).

The minimum area covered by a partial-depth repair treatment should be 1 foot by 1 foot (IDOT 2010). The performance of partial-depth repairs is typically similar under different traffic conditions (IDOT 2010).

Table 18 summarizes the life expectancy and cost data for partial-depth repairs.

Table 18. Partial-depth repair life expectancy and cost data

Reference	Life Expectancy (yrs)	Cost
NDOR 2002	10-15	$95-$110/yd^2
SDDOT 2010	5-15	NR
IDOT 2010	5-15	NR

The minimum life expectancy for partial-depth repairs was 5 years while the maximum was 15 years. The cost of partial-depth repair was from $95 to $110 per square yard (NDOR 2002).

Joint Sealing/Resealing

Joint sealing/resealing is a treatment that involves sealing transverse joints in PCC pavement. This technique is utilized to stop water infiltration into pavement foundations (Shahin 1994 and IDOT 2010). The treatment is intended to reduce faulting, pumping, and spalling (IDOT 2010).

The treatment should be applied to slightly deteriorated jointed plain concrete pavements with narrow transverse joints (IDOT 2010). The performance of this treatment is not affected by different traffic volumes or percentage of trucks (IDOT 2010).

Table 19 summarizes the life expectancy and cost data for joint sealing/resealing as reported by different DOTs.

Table 19. Joint sealing/resealing life expectancy and cost data

Reference	Life Expectancy (yrs)	Cost	Remarks
NDOR 2002	4-7	$1.00-$1.75/lin. ft^2	None
SDDOT 2010	4-20	NR	4 to 15 years for hot-poured asphalt sealant; 10 to 20 years for silicone sealant
IDOT 2010	4-8	NR	4 and 8 years for hot-poured asphalt sealant; approximately 8 years if silicone sealant used

The minimum life expectancy reported was 4 years while the maximum was 20 years. Life expectancy of joint sealing depended on the sealant material used.

Longitudinal Crack Repair

Longitudinal cracking appears in continuous reinforced concrete (CRC) pavements. Cracks are accompanied by spalling and D-cracks (IDOT 2010).

Longitudinal crack repair is a maintenance treatment that involves milling cracks to a depth of 2 to 3 inches with a width of 12 to 24 inches (IDOT 2010). An HMA mixture is then used to fill the milled area. It is more economical to treat longitudinal cracks rather than patching distressed locations.

This treatment should not be applied to pavement that has excessive faulting or has structurally deteriorated (IDOT 2010). The life expectancy of longitudinal crack repair was from 5 to 8 years (IDOT 2010)

Full-Depth Repairs

Full-depth repair is a treatment method that involves repairs through the full thickness of the PCC slab (IDOT 2010). Full-depth removal and replacement is done to existing deteriorated PCC pavements (IDOT 2010). When the entire slab is replaced, the treatment is referred to as slab replacement.

Full-depth patching is used to repair a variety of distresses, most of which occur near joints or cracks such as corner breaks and D-cracking, joint spalling, and longitudinal and transverse cracks (Shahin 1994 and IDOT 2010). Deterioration of a reflected joint or crack in an asphalt concrete overlay is also a candidate for full-depth patching of the underlying concrete pavement (Shahin 1994).

When a full-depth patch is performed adjacent to a joint or crack, the load transfer across the joint or crack should be restored (IDOT 2010). This treatment is not cost effective when distresses are widespread within the pavement segment (IDOT 2010).

Table 20 summarizes the life expectancy and cost data for full-depth repairs.

Table 20. Full-depth repair life expectancy and cost data

Reference	Life Expectancy (yrs)	Cost
NDOR 2002	10-15	\$95-\$110/yd^2
SDDOT 2010	10-15	NR
IDOT 2010	10-15	NR

The expected life of full-depth repairs was typically from 10 to 15 years. The cost of full-depth repairs was from $95 to $110 per square yard (NDOR 2002)

2.5. Rehabilitation Treatments for PCC Pavements

Bonded Concrete Overlay

Bonded concrete overlay is a PCC treatment method that involves the direct placement of a new concrete overlay on the existing PCC pavement (IDOT 2005a and MoDOT 2002). The bond is created by placing saw cuts in the overlay at underlying locations such as joints, patches, and working cracks (IDOT 2005a and MoDOT 2002).

IDOT (2005a) and MoDOT (2002) recommend using this treatment on a good performing pavement. The purpose of this treatment is to increase the structural capacity of the pavement and restore the ride quality.

The thickness of bonded concrete overlays should be designed according to the existing design procedures. However, IDOT (2005a) recommends a minimum thickness of two inches for overlays while MoDOT (2002) recommends a typical thickness of three to five inches. State highway agencies have different practices and design procedures. Local agencies should use their practice and experience.

The following cases should not be considered for bonded concrete overlay (IDOT 2005a):

- Pavements with D-cracks
- Pavements with patches greater than 2 percent
- Pavements with HMA overlays

Unbonded Concrete Overlay

Unbonded concrete overlay is a similar technique to bonded concrete overlay except that the concrete layer can move independently (IDOT 2005b). The overlay is separated from the existing PCC layer by a bond breaker or separation interlayer (IDOT 2005b and MoDOT 2002). The unbonded overlay may be designed as a jointed or continuous concrete pavement (MoDOT 2002). The overlay also can be plain or reinforced concrete (MoDOT2002). The separation interlayer is constructed of HMA. The older PCC layer acts a stiff base layer while the overlaid layer acts as the primary structural layer (MoDOT 2002). The use of unbonded concrete overlays works on preventing reflective cracking (IDOT 2005b).

IDOT (2005b) recommends determining the thickness of the overlay case-by-case according to the pavement type, condition of the interlayer, and type of road. However, the typical thickness of continuous reinforced concrete overlays recommended by IDOT (2005b) is 9 to 10 inches. IDOT (2005b) recommends a minimum thickness of the HMA interlayer of 4 inches while

MoDOT (2002) usually uses a 1 inch thickness for the HMA interlayer. The design procedures and practices are different from one agency to another.

IDOT (2005b) reported that unbonded concrete overlays had a life expectancy of more than 20 years.

HMA Overlay with Rubblization/Break/Crack and Seat

HMA overlay is one of the most common PCC pavement rehabilitation methods. It is necessary to destroy the PCC slab before the application of an HMA overlay to protect the overlaying layers from reflective cracking and distress transfer. Different fracturing techniques, such as rubblization, crack and seat, and break and seat, can be used to destroy the PCC slab.

The break and seat fracturing technique is the most suitable for jointed reinforced concrete pavement (JRCP), while crack and seat is the most suitable for jointed plain concrete pavement (JPCP). Rubblization can be applied to any type of PCC pavement. Rubblization is defined as "breaking the existing pavement into pieces and overlaying with HMA" (Ceylan et al. 2008).

Maher et al. (2005) reported 15 to 20 years life expectancy for HMA overlays above rubblized or crack and seat concrete. Cost of rubblization or any fracturing method depended on project location and size. The cost of rubblization was from $12.50 to $25.00 per cubic yard (Maher et al. 2005).

Table 21 summarizes the agency costs for HMA overlays using different fracturing techniques for non-Interstate roads (Ahmed 2012).

Table 21. Agency costs for HMA overlay using different fracturing techniques

	Unit Cost ($/ Lane-Mile) - 2010 Equivalent $				**Sample**
Treatment Type	**Mean**	**Minimum**	**Maximum**	**Std. Dev.**	**Size**
Repair PCC and HMA Overlay	$491,865	$2,883	$844,367	$345,803	15
Crack and Seat PCC and HMA Overlay	$440,847	$143,415	$324,704	$114,233	7
Rubblize PCC and HMA Overlay	$757,057	$425,913	$1,256,176	$239,717	12

Source: Ahmed 2012

The data originated from INDOT databases and was calculated into a unit cost (Ahmed 2012). In addition, all of the costs were brought to the 2010 equivalent cost (Ahmed 2012). Note how different fracturing techniques can control project costs significantly.

Dowel-Bar Retrofit (DBR)

Dowel-bar retrofit (DBR) is considered a PCC rehabilitation technique that involves the removal of pavement slots across the joint or crack (MoDOT 2002). The treatment is a load transfer method that works on transferring loads across joints and working cracks (MoDOT 2002).

Dowel bars are placed instead of the removed slots and then backfilled with new concrete or grout material. DBR addresses transverse cracks and transfers the load evenly across the crack or joint (MoDOT 2002 and IGGA 2010).

The life expectancy of DBR was 10 to 15 years (NDOR 2002); however, SDDOT (2010) reported 15 to 20 years life expectancy.

2.6. State DOT Maintenance and Rehabilitation Practices

Michigan DOT (MDOT)

The Michigan DOT (MDOT) developed a Capital Preventive Maintenance Manual that helps in selecting the appropriate preventive maintenance treatment method. MDOT considers five main factors when selecting a treatment method:

- Remaining service life (RSL)
- Distress index (DI)
- International roughness index (IRI)
- Ride quality index (RQI)
- Rut depth

Generally, the RSL of any pavement segment should be greater than two years to apply a preventive maintenance treatment to it. If the RSL is less than two years, it is better to apply a rehabilitation treatment method.

While some exceptions can be made regarding use of the following threshold values, Tables 22 and 23 show the different threshold values adopted by MDOT for each asphalt and composite pavement treatment method and each PCC pavement treatment method, respectively.

Table 22. Michigan DOT asphalt and composite pavement treatment method thresholds

Treatment Type	Pavement Type	Thresholds				
		RSL	DI	RQI	IRI	Rut (in.)
Non-Structural HMA overlay	Flexible	3	<40	<70	<163	<0.5
	Composite	3	<25	<70	<163	<0.5
Surface Milling with Non-Structural Overlay	Flexible	3	<40	<80	<212	<1
	Composite	3	<30	<80	<212	<1
Chip Seal	Flexible (double)	5	<30	<54	<107	<1/8
	Flexible (single)	6	<25	<54	<107	<1/8
	Composite (double)	5	<15	<54	<107	<1/8
Microsurfacing	Flexible (multiple or heavy single)	5	<30	<54	<107	<1
	Flexible (regular single)	10	<15	<54	<107	<1
	Composite (double)	5	<15	<54	<107	<1
Crack Treatment	Flexible	10	<15	<54	<107	<1/8
	Composite	10	<5	<54	<107	<1/8
Ultra-Thin HMA Overlay	Flexible	7	<30	<54	<107	<1/8
	Composite	7	<20	<54	<107	<1/8
Paver-Placed Surface Seal	Flexible	5	<30	<62	<132	<1/4
	Composite	5	<15	<62	<132	<1/4

Table 23. Michigan DOT PCC pavement treatment method thresholds

Treatment Type	Thresholds			
	RSL	DI	RQI	IRI
Full Depth Concrete Pavement Repair	3	<20	<54	<107
Concrete Joint Resealing	10	<15	<54	<107
Concrete Crack Sealing	10	<15	<154	<107
Diamond Grinding	12	<10	<54	<107
Dowel-Bar Retrofit	10	<15	<54	<107
Concrete Pavement Restoration	3	<40	<80	<212

The application of surface milling with non-structural overlay, microsurfacing, crack sealing, and crack filling can be done with higher RQI and IRI than recommended in urban locations that are taking corrective actions regarding the ride quality.

Crack treatment includes both crack sealing and crack filling maintenance treatments.

A paver-placed surface seal is a treatment method that uses a polymer-modified asphalt emulsion with the application of a gap-graded ultra-thin HMA surface course. This treatment method is used to reduce water intrusion and improve pavement friction. It can also be used to improve the qualities of ride, noise, and skid.

Concrete pavement restoration combines diamond grinding with full-depth concrete pavement repair.

Additional treatments can be applied to improve the rigid pavement condition such as spall repair, dowel-bar retrofit, crack seal, and joint resealing (MDOT 2003).

Each treatment is listed in the manual with the following information:

- Description
- Purpose
- Existing pavement condition
- Existing pavement surface preparation
- Performance
- Performance limitations

User of this manual need to examine the existing pavement condition before selecting the proper treatment. Using the thresholds for RSL, DI, RQI, IRI, and rut depth might not lead to the optimum decision. The DI combines several types of distresses to form one index that captures the pavement condition. Using the distress index to decide which treatment should be applied without looking at each existing distress may lead to an undesirable result. The manual does not establish a selection framework when more than one feasible treatment is available.

Minnesota DOT (MnDOT)

The Minnesota DOT (MnDOT) developed decision trees for both flexible (bituminous and bituminous over concrete/BOC) and rigid (concrete) pavements (MnDOT 2012a and 2012b). Each decision tree ends with treatments that are categorized (and color coded) as either preventive maintenance, rehabilitation, reconstruction, or do nothing.

For bituminous and BOC pavement preventive maintenance treatments, the decision tree ends with chip seal, microsurfacing, crack seal, crack fill, rut fill, thin overlay, or thin mill and overlay. For bituminous and BOC pavement rehabilitation treatments, the decision tree ends with thin overlay, thick overlay, medium mill and overlay, or thick mill and overlay.

For concrete pavement preventive maintenance treatments, the decision tree ends with joint seal, plane (diamond grinding), minor concrete pavement rehabilitation (CPR), or minor CPR and plane. For concrete pavement rehabilitation methods, the decision tree ends with major CPR, major CPR and plane, or thick overlay.

MnDOT (2012a) uses the following distresses to select a proper bituminous/BOC pavement treatment:

- Rutting
- Multiple cracking (a pattern of cracks dividing the pavement into rectangular blocks per MnDOT 2003)
- Alligator cracking
- Transverse cracking
- Longitudinal cracking

The bituminous/BOC pavement decision tree considers the different types of distresses, pavement age, last rehabilitation treatment applied, existence of curbs, AADT, and RQI. The average annual daily traffic (AADT) is considered when making a decision between chip seal and microsurfacing.

MnDOT (2012b) uses the following distresses to select a proper concrete pavement treatment:

- Transverse spall
- Longitudinal spall
- D-cracking
- Broken panel
- Patch greater than 5 square feet

The concrete pavement decision tree also uses the pavement age, last rehabilitation applied, and RQI.

Regardless of pavement type (bituminous/BOC or concrete) MnDOT uses and RQI, pavement quality index (PQI), and surface rating (SR) with different trigger values (which are the same for both pavement types) according to the road classification. Table 24 summarizes the threshold values for RQI, PQI, and SR according to road classification.

Table 24. MnDOT threshold values according to road classification

Road Type	RQI	SR	PQI
Rural Principal Interstate	3.0	2.7	3.0
Rural Principal Arterial	3.0	2.7	2.9
Rural Minor Arterial	2.8	2.5	2.8
Rural Major Collector	2.8	2.5	2.6
Rural Minor Collector	2.8	2.5	2.6
Rural Local	2.7	2.4	2.6
Urban Interstate	3.1	2.7	3.0
Urban Principal Arterial Freeway	3.1	2.7	2.9
Urban Principal Arterial	2.8	2.5	2.9
Urban Minor Arterial	2.7	2.4	2.8
Urban Collector	2.6	2.4	2.6
Urban Local	2.5	2.4	2.6

Source: MnDOT 2012a and 2012b

Table 25 summarizes the scenarios that lead to each preventive maintenance treatment for bituminous/BOC pavement.

Table 25. MnDOT bituminous/BOC pavement preventive maintenance thresholds

Treatment	MTC	SLTC	SLTC +MTC +STC	RQI	Rutting	Pavement Age (yrs)	LR	Curbs	AADT
Rut Fill	-	-	-	>threshold value according to road classification	>10%	-	Not a Rut fill	-	
Thin Mill and Overlay	-	-	-			-	Rut Fill	-	
Thin Mill and Overlay	-	-	<60	>2.6	-	-	-	Yes	
Thin Overlay	-	-	<60	>2.6	-	-	-	No	
Crack Seal	≤4.0	≥13	<40	>threshold value according to road classification	<10%	2-5	OVL, MOVL, RCLM, REC or CIB	-	
Crack Fill	≤50	≥13	<40			5-8		-	
Microsurfacing	-	-	-			≥7	**Not** OVL, MOVL, RCLM, REC or CIB	-	>10000
Chip Seal									<10000
Microsurfacing	>50	<13	>40				OVL, MOVL, RCLM, REC or CIB	-	>10000
Chip Seal							-	-	<10000

Source: MnDOT 2012a

AADT: Average annual daily traffic
AC: Alligator crack
CIB: Cold in-place recycling
LR: Last rehabilitation applied
MC: Multiple cracks
MOVL: Mill with overlay
MTC: Medium transverse crack
OVL: Overlay
RCLM: Reclamation
REC: Reconstruction
SLC: Severe longitudinal crack
SLTC: Slight transverse crack
STC: Severe transverse crack

Bituminous/BOC pavement rehabilitation treatment or reconstruction activities are adopted whenever the threshold values for one of the cracking distresses is as follows:

- Alligator cracking greater than 4 linear feet
- Severe longitudinal cracking greater than 20 feet
- Severe transverse cracking greater than 20 feet
- Multiple cracking greater than 20 feet

Table 26 summarizes the thresholds for each rehabilitation treatment or reconstruction activity.

Table 26. MnDOT bituminous/BOC pavement rehabilitation treatment and reconstruction thresholds

<table>
<tr><th>Treatment</th><th>Principal Arterial</th><th>RQI</th><th>SR</th><th>Bituminous over Concrete</th><th>Curbs</th></tr>
<tr><td>Thick Overlay</td><td rowspan="2">No</td><td rowspan="2">>2</td><td rowspan="2">>Threshold according to road classification</td><td rowspan="2">-</td><td>No</td></tr>
<tr><td>Thick Mill and Overlay</td><td>Yes</td></tr>
<tr><td>Thick Overlay</td><td rowspan="2">Yes</td><td rowspan="2">>2.3</td><td rowspan="2">>Threshold according to road classification</td><td rowspan="2">-</td><td>No</td></tr>
<tr><td>Thick Mill and Overlay</td><td>Yes</td></tr>
<tr><td>Full Pavement Replacement (BAB) (Urban)</td><td rowspan="2">No</td><td rowspan="2">≤2</td><td rowspan="2">-</td><td rowspan="2">No</td><td>Yes</td></tr>
<tr><td>Full Pavement Replacement (BAB) (Rural)</td><td>No</td></tr>
<tr><td>Full pavement Replacement (CD Unbonded OL) (Rural)</td><td rowspan="2">No</td><td rowspan="2">≤2</td><td rowspan="2">-</td><td rowspan="2">Yes</td><td>No</td></tr>
<tr><td>Full Pavement Replacement (CD) (Urban)</td><td>Yes</td></tr>
<tr><td>Full Pavement Replacement (BAB) (Urban)</td><td rowspan="2">Yes</td><td rowspan="2">≤2.3</td><td rowspan="2">≥Threshold according to road classification</td><td rowspan="2">No</td><td>Yes</td></tr>
<tr><td>Full Pavement Replacement (BAB) (Rural)</td><td>No</td></tr>
<tr><td>Full Pavement Replacement (CD Unbonded OL) (Rural)</td><td rowspan="2">Yes</td><td rowspan="2">≤2.3</td><td rowspan="2">≥Threshold according to road classification</td><td rowspan="2">Yes</td><td>No</td></tr>
<tr><td>Full Pavement Replacement (CD) (Urban)</td><td>Yes</td></tr>
</table>

Source: MnDOT 2012a

BAB: Bituminous aggregate base
CD: Concrete doweled
OL: Overlay

Utah DOT (UDOT)

The Utah DOT (UDOT) developed a pavement management system that utilizes Deighton's Total Infrastructure Asset Management Software (dTims) to maintain their pavement assets (UDOT 2009). The system developed focuses on forecasting the future condition and suggesting an optimum set of treatment strategies. The system has three levels of management, which are Interstate, level one, and level two roads. The main difference between a level one and level two road is the AADT value. Level one is roads that have AADT greater than 2,000 while level two is roads that have AADT less than 2,000.

Table 27 and 28 summarize the distresses for asphalt and PCC pavement, respectively.

Table 27. UDOT distresses and limitations for each asphalt treatment

Treatment	Distress(es) and limitations
Crack Sealing	Working crack with movement greater than or equal to 0.1 in.
Crack Filling	Cracks with movement less than or equal to 0.1 in.
Full-depth crack repair (combined with cold latex in case of small cracks)	Excessive and close cracks
Fog Seal/Rejuvenation	Small cracks and surface voids and low to moderate weathering or raveling; should not be used if pavement has low skid resistance, rutting, or shoving; can be applied to Interstate but with high caution because of the heavy traffic
Chip Sealing	Slight raveling and surface wear; longitudinal and transverse cracking with a minor amount of secondary cracking; slight to moderate flushing or polishing and/or occasional patch in good condition; should not be used with temperature below 65 °F; noise increases after application

Source: UDOT 2009

Table 28. UDOT distresses and limitations for each PCC treatment

Treatment	Purpose, addressed distress(es), and/or limitations
Joint Sealing and Joint Spall repair	Should be applied when joint sealant is deteriorated or missing; should not be applied if pavement is heavily deteriorated
Diamond Grinding	Distresses addressed are joint faulting, wheel path rutting, minor slab warping at joints, polishing, and light scaling; can be applied if IRI is greater than 140 or average skid value is less than or equal to 30

Source: UDOT 2009

UDOT uses four indices for asphalt pavements:

- Ride index based on the IRI
- Rut index based on pavement rutting
- Environmental cracking index based on transverse, longitudinal, and block cracking
- Wheel-path cracking index

UDOT (2009) uses four indices for concrete pavements:

- Ride index based on the IRI
- Structural cracking index
- Fault index
- joint index based on joint spalling

Joint index based on joint spallingBased on asphalt or concrete pavement indices, an overall condition index is calculated to represent the pavement condition. Treatments are triggered based on the value of each index. For example, an asphalt major rehabilitation treatment will be triggered if the wheel-path cracking index is less than or equal 55. However, the model developed does not specify a certain rehabilitation treatment.

South Dakota DOT (SDDOT)

The South Dakota DOT (SDDOT) has treatment selection guidelines for both flexible and rigid pavements. The treatment selection is based on the distress type, severity, and extent.

SDDOT (2010) addresses the following distresses for flexible pavements:

- Fatigue cracking
- Transverse cracking
- Patch deterioration
- Block cracking
- Rutting
- Roughness (IRI)

Table 29 shows the a sample of SDDOT distress severity and extent thresholds for flexible pavement distress types.

Table 29. Sample of SDDOT flexible pavement distress severity and extent thresholds

Distress Type	Severity Level	Extent
Fatigue Cracking	Low: Fine parallel cracks in wheel path	Low: 1 to 9% of wheel path is affected
	Medium: Alligator pattern clearly developed	Moderate: 10 to 24% of wheel path affected
	High: Alligator pattern cracking clearly developed with spalling and distortion	High: 25 to 49 % of wheel path affected
		Extreme: More than 49% of wheel path affected
Transverse Cracking	Low: Crack width less than 0.25 in. or routed and sealed crack width less than 0.5 in.	Low: Crack spacing greater than 50 ft average spacing
	Medium: Crack width between 0.25 and 1 in. and/or depression caused by crack is less than 0.25 in.	Moderate: Crack spacing less than 50 ft and greater than 25 ft average spacing
	High: Crack width greater than 1 in. or crack width greater than 0.25 in. and depression caused by crack greater than 0.25 in.	High: Crack spacing less than 25 ft and greater than 12 ft average spacing
		Extreme: Crack spacing less than 12 ft average spacing
Patching and patch deterioration	Low: No visual distress and riding is smooth	Low: 1 to 9% of the section affected
	Medium: Patch has low or medium distress and/or notable roughness	Moderate: 10 to 24% of the section affected
	High: Patch has high-severity distress and/or high level of roughness	High: 25 to 49% of the section affected
		Extreme: More than 49% of the section affected
Rutting	Low: Rut depth less than 0.125 in.	Low: 1 to 9% of the section affected
	Moderate: rut depth is between 0.125 and 0.25 in.	Moderate: 10 to 24% of the section affected
	High: rut depth is between 0.25 and 0.5 in.	High: 25 to 49% of the section affected
	Extreme: rut depth greater than 0.5 in.	Extreme: More than 50% of the section affected

Source: SDDOT 2010

Table 30 shows part of the treatment selection matrix developed by SDDOT for transverse cracking.

Table 30. Part of SDDOT flexible pavement treatment selection decision matrix for transverse cracking

Pavement Distress	Severity Level [1]	Extents [2]	Crack Treating	Crack Sealing	Crack Leveling	Fog Seals	Scrub Seals
Transverse Cracking	Low	Low	R	R	NR	F	NR
		Moderate	R	R	NR	F	NR
		High	F	F	NR	F	NR
		Extreme	NR	NR	NR	F	NR
	Medium	Low	R	R	F	F	NR
		Moderate	R	R	F	F	NR
		High	F	F	F	NR	NR
		Extreme	NR	NR	NR	NR	NR
	High	Low	NR	NR	R	NR	NR
		Moderate	NR	NR	R	NR	NR
		High	NR	NR	R	NR	NR
		Extreme	NR	NR	NR	NR	NR

R	Recommended treatment
F	Feasible Treatment
NR	Treatment is not recommended

Source: SDDOT 2010 (For Severity Level[1] and Extents[2], see Transverse Cracking rows in Table 29)

Feasible treatments are available according to the distress type, severity level, and extent. SDDOT classifies treatment feasibility into three categories: recommended, feasible, and not recommended. For example, microsurfacing (not shown in Table 30) is a feasible treatment for low-severity rutting with extreme extent while chip seal (also not shown in Table 30) is the recommended treatment for this particular case (SDDOT 2010). The major drawback to the SDDOT treatment selection matrix is that it does not take into consideration the combination of two or more existing distresses.

The pavement preservation guidelines developed by SDDOT (2010) include the following treatments for flexible pavements:

- Crack treating
- Fog seal
- Flush seal
- Scrub seal
- Rejuvenators
- Microsurfacing
- Asphalt surface treatments
- Thin HMA overlay
- Cold milling
- Crack leveling
- Rut filling
- Spray patching

Similarly, the preservation guidelines include the following treatments for rigid pavements (SDDOT 2010):

- Crack sealing
- Joint resealing
- Diamond grinding
- Diamond grooving
- Full-depth repair
- Partial-depth repair
- Dowel-bar retrofit
- Cross stitching
- Pavement sub-sealing/ under-sealing
- Pavement jacking

The following distresses are addressed for rigid pavements:

- D-cracking
- Joint spalling
- Corner cracking
- Longitudinal cracking
- Punchouts for CRC pavements only
- Joint seal damage
- Faulting
- Roughness

Illinois DOT (IDOT)

The Illinois DOT (IDOT) has developed pavement management guidelines to preserve the pavement investment and maintain a high level of service (IDOT 2010). IDOT identified traffic, environment and aging, materials, and moisture as the four causes of asphalt pavement deterioration. As for rigid pavements, traffic environment and materials, construction, incompressible materials, and moisture are the five main causes of deterioration.

IDOT employs five steps to select the most appropriate treatment strategy.

1. Gathers the pavement information.
2. Assess the information gathered.
3. Evaluate pavement data.
4. Identify feasible preservation treatments.
5. Select the most appropriate preservation treatment.

Pavement information is gathered, such as pavement type, pavement age, design life, traffic, and pavement materials. The selection of the most appropriate treatment is subject to several constraints such as the availability of qualified contracts, initial costs, facility downtime, availability of quality materials, and so forth (IDOT 2010).

Tables 31 and 32 show the IDOT decision matrices for flexible and rigid pavements, respectively.

Table 31. Illinois DOT flexible pavement treatment selection decision matrix

Pavement Conditions	Distress Levels [1]	Crack Filling	Crack Sealing	Fog Seal [2]	Sand Seal [2]	Slurry Seal	Micro-surfacing	Chip Seal	Cape Seal	CIR [2]	HIR [2]	SMART	Ultra- Thin Bonded Wearing Course	Cold Mill
Alligator/ Fatigue Cracking [3]	L1	F	F	NR	NR	F	F	F	F	F	F	F	F	NR
	L2, L3, L4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Block Cracking	M1	R	R	F	R	R	R	R	R	R	R	F	F	F
	M2	R	R	NR	NR	F	NR	F	F	F	F	NR	NR	NR
	M3, M4	F	F	NR	NR	NR	NR	NR	NR	F	F	NR	NR	NR
"Stable" Rutting [4]	N1, N2	NR	NR	NR	NR	F	R	F	F	R	R	R*	F	F
	N3	NR	NR	NR	NR	NR	F	NR	NR	R	R	R*	NR	F
Joint Reflection and Transverse Cracking [5]	O1	NR	NR	F	R	F	R	R	R	F	F	R**	F	F
	O2, O3	R	R	NR	NR	NR	F	F	F	F	F	F	NR	NR
	O4, O5	F	F	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Overlayed Patch Reflective Cracking	P1, P2, P3, P4, P5	F*	F*	F*	F*	F*	F*	F*	F*	F*	F*	F*	F*	F*
Longitudinal / Center of Lane Cracking	Q1	R	R	F	F	F	F	F	F	F	F	F	F	F
	Q2, Q3	R	F	NR	NR	NR	F	F	F	F	F	F	F	F
	Q4, Q5	NR	NR	NR	NR	NR	NR	NR	NR	F	F	NR	NR	NR
Reflective Widening Crack	R1	R	R	F	F	F	F	F	F	F	F	F	F	F
	R2, R3	F	F	NR	NR	F	F	F	F	F	F	F	NR	NR
	R4, R5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Centerline Deterioration	S1, S2, S3, S4	F*	F*	F*	F*	F*	F*	F*	F*	F*	F*	F*	F*	F*
Edge Cracking	T1	F	F	F	R	F	F	R	F	R	R	R**	F	F
	T2	F	F	NR	NR	NR	F	F	F	F	F	F	NR	NR
	T3, T4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Permanent Patch Deterioration	U1, U2, U3, U4	F*	F*	F*	F*	F*	F*	F*	F*	F*	F*	F*	F*	F*
Shoving, Bumps, Sags, and Corrugation	V1	NR	NR	NR	NR	NR	F	F	F	R	R	R	F	R
	V2, V3	NR	NR	NR	NR	NR	NR	NR	NR	R	R	R	NR	R
Weathering/ Raveling	W1, W2	NR	NR	F	F	R	R	R	R	F	F	F	F	F
	W3, W4	NR	NR	NR	NR	F	F	F	F	R	R	R*	NR	NR
Reflective D-Cracking	X1, X2, X3	NR	NR	NR	NR	NR	NR	NR	NR	F	F	NR	F	F
Friction	Poor	NR	NR	NR	R	R	R	R	R	F	F	R	R	F
ADT	< 5,000	R	R	R	R	R	R	R	R	R	R	R	R	R
	5,000 – 10,000	R	R	F	F	F	R	R	R	F	R	R	R	R
	> 10,000	R	R	NR	NR	NR	F	F	F	NR	R	R	R	R
Relative Cost	($ to $$$$)	$	$	$	$$	$$	$$	$$	$$	$$$	$$$	$$$	$$$	$

Source: IDOT 2010

Table 32. Illinois DOT rigid pavement treatment selection decision matrix

Pavement Conditions	Distress Levels[1]	Crack Sealing	Joint Resealing	Diamond Grinding	Diamond Grooving	Ultra- Thin Bonded Wearing Course	Full-Depth Repairs	Partial-Depth Repairs	LTR[2, 3]
D-cracking	A1, A2	NR	F	NR	NR	F	NR	NR	NR
	A3	NR	NR	NR	NR	NR	F	R	NR
	A4, A5	NR	NR	NR	NR	NR	R	NR	NR
Transverse Cracking	B1	NR	NR	NR	NR	R	NR	NR	NR
	B2, B3	R	NR	NR	NR	F	F	NR	F
	B4, B5	F	NR	NR	NR	NR	F	NR	F
Joint Deterioration	C1, C2	NR	R	R	NR	F	NR	F	F
	C3, C4	NR	F	R*	NR	F	F	R	F
Centerline Deterioration	D1	NR	R	NR	NR	R	NR	NR	NR
	D2	NR	F	NR	NR	F	NR	R	NR
	D3	NR	NR	NR	NR	NR	F	R	NR
Longitudinal Cracking	E1, E2	R	NR	NR	NR	F	F	NR	NR
	E3, E4	F	NR	NR	NR	F	R	NR	NR
Edge Punchouts (CRCP)	F1, F2, F3	NR	NR	NR	NR	F	R	NR	NR
Faulting	G1, G4	NR	R	F	NR	F	NR	NR	NR
	G2, G5	NR	F	R	NR	F	NR	NR	R
	G3, G6	NR	NR	R*	NR	NR	NR	NR	R
Corner Breaks (JPCP)	H1, H2	R	NR	NR	NR	F	F	NR	NR
	H3	NR	NR	NR	NR	NR	R	NR	NR
Map Cracking and Scaling	I1	NR	NR	F	NR	R	NR	NR	NR
	I2	NR	NR	F	NR	R	NR	F	NR
	I3	NR	NR	F	NR	F	NR	F	NR
Popouts/High Steel	J1, J2, J3	NR	NR	NR	NR	F**	NR	F**	NR
Permanent Patch Deterioration	K1, K2, K3	F**	F**	F**	F**	F**	F**	F**	F**
Ride	IRI > 140 in/mi	NR	NR	R	NR	F	NR	NR	F*
Skid	Poor	NR	NR	R	R	R	NR	NR	NR
Relative Cost	($ to $$$$)	$	$	$$	$$	$$$	$$$$	$$$	$$$

Source: IDOT 2010

As for flexible pavements, the following distresses are considered by IDOT (2010).

- Alligator cracking
- Block cracking
- Rutting
- Transverse cracking
- Longitudinal cracking
- Reflective widening cracking
- Centerline deterioration
- Edge cracking
- Patch deterioration
- Shoving
- Raveling
- Reflective D-cracking

In addition, friction and average daily traffic are considered as decision parameters.

As for rigid pavements, the following treatments are considered by IDOT (2010):

- D-cracking
- Transverse cracking
- Joint deterioration
- Centerline deterioration
- Longitudinal cracking
- Edge punchouts
- Faulting
- Corner breaks
- Map cracking
- Popouts
- Patch deterioration

In addition, ride quality in terms of IRI and skid resistance are considered decision parameters to select the most appropriate treatment (IDOT 2010).

The treatment selection decision is divided into three categories: recommended, feasible, and not recommended. For example, microsurfacing is a feasible treatment for low-severity rutting while a recommended treatment for low-severity block cracking. Microsurfacing also is not recommended for moderate to severe alligator cracking.

IDOT (2010) uses the following treatments to address flexible pavement distresses:

- Crack filling
- Crack sealing
- Fog seal
- Sand seal
- Slurry seal
- Microsurfacing
- Chip seal
- Cape seal
- Cold in-place recycling
- Hot in-place recycling
- Surface maintenance
- Ultra-thin bonded wearing course
- Cold mill

IDOT (2010) uses the following treatments to address rigid pavements distresses:

- Crack sealing
- Joint resealing
- Diamond grinding
- Diamond grooving
- Ultra-thin bonded wearing course
- Full-depth repairs
- Partial-depth repairs
- Load transfer restoration

2.7. Level of Service Indicators

Different LOS indicators have been used by DOTs. Some DOTs developed their own indicators while others use pre-developed and widely accepted ones. There are many functional and structural LOS indicators that can be found in the literature. The most common are reported and summarized in this section.

The main role of LOS indicators is to describe the pavement functional or structural condition. In addition, LOS indicators can be used to determine the required pavement maintenance or rehabilitations actions.

The pavement condition index (PCI) is one of the most widely used indexes by state highway agencies. The PCI was first developed by the U.S. Army Corps of Engineers (Shahin and Walther 1990). The PCI is a numerical index that ranges from 0 to 100, while 0 indicates a failed pavement and 100 indicates a perfect condition pavement. The calculation of the PCI value is based on the distress type, distress severity, and distress extent. The PCI has been used and modified by many state highway agencies.

The pavement condition rating (PCR) is a value that ranges from 0 to 100. A pavement segment that receives 100 indicates that the segment is in a perfect condition and has no distresses. The value of the PCR is calculated using the deduct values for each pavement distress. The PCR considers the distress type, distress severity, and the extent of the distress (Kay 1992). The deduct values that are used to calculate the PCR are different from one DOT to another.

Remaining service life (RSL) is defined as the time measured in years that a pavement section takes to reach an unacceptable condition from the latest condition survey year (Dawson 2012). The RSL is equal to or less than the design life of a pavement section (Dawson 2012).

Pavement serviceability refers to the capability of the pavement to serve the existing traffic in its existing condition (Huang 1993). The IRI and the present serviceability index (PSI) are the two methods used to evaluate pavement serviceability. The PSI was developed at the American Association of State Highway Officials (AASHO) Road Test in 1960. The PSI is based on the pavement roughness and the distress conditions (Huang 1993).

IRI is used to measure pavement roughness and ride quality. Roughness can be defined as "variation in surface elevation" (Sayers et al. 1986). Pavement roughness has a direct effect on the ride quality, safety, and user costs. A smooth pavement will have 0 index. The value of the index increases as the roughness of the road increases. The IRI can be used as a major determinant for the user costs (Sayers et al. 1986).

The ride quality index (RQI), similar to the IRI, is used to measure the pavement roughness. The RQI is determined using the IRI values. MnDOT uses two different equations to determine the RQI with one equation for bituminous pavement and the other for concrete pavement. The value of the RQI ranges from 0 to 5. A pavement segment with an RQI value of 5 indicates that the segment has a good ride quality (MnDOT 2006.

The distress index (DI) is a measure of the quantity and severity of different distresses that exist in a pavement section. Distresses are combined together and the severity of each distress is taken into account. The DI value is calculated by giving points to each distress according to its type and severity. MDOT has developed a set of deduct points for each distress type, quantity, and severity (Dawson 2012). The severity level and the extent of most of the distresses can be expressed linguistically using the terms low, medium, and high. The Washington State DOT (WSDOT) is one of the first DOTs that used the deduct values for each distress (Flora 2009).

Surface rating (SR) is a measure developed and used by MnDOT to quantify the pavement distress. Technicians can access digital images captured by a traveling van to determine the type, extent, and severity of a defect. The rating process is done by two people to maintain the consistency. However, some distresses can be difficult to quantify because of the two-dimensional (2D) images (MnDOT 2006).

Many state highway agencies have developed their own indexes. LOS indicators vary in their complexities. Some indicators can be determined using simple mathematical formulas and visual inspection while others may require the use of automated machines and laser scanners.

Most local agencies depend on visual inspection or data collected by the DOT. It may not be feasible or reasonable for local agencies to use complex and highly accurate LOS indicators. The use of simple LOS indicators need to be considered when developing a treatment selection framework for local agencies.

3. SURVEY QUESTIONNAIRE ANALYSIS

An electronic survey questionnaire was developed and sent to Iowa city and county engineers to learn about their practices and needs. The survey was designed to figure out the most prevailing pavement distresses and ask about the treatments used to address different distresses.

The survey consisted of 15 questions related to pavement distress data collection, common preservation and rehabilitation treatments applied, and decision-making frameworks. The first two questions in the electronic survey were developed to collect contact information for follow-up purposes. The objectives of questions 3 through 8 were to investigate the pavement distress data collected and the common existing pavement distresses. Questions 9 through 12 were related to preservation and rehabilitation treatment application. The last three questions (13 through 15) were related to treatment selection frameworks if existing.

The total number of survey responses received was 74. The number of responses for each question is different because partially completed surveys were recorded and analyzed.

This chapter is dedicated to describing and analyzing the survey responses from the engineers. The first section summarizes the responses to questions related to distress data collection and common distresses experienced by city and county engineers, as well as the maintenance and rehabilitation treatment usage for both flexible and rigid pavements. The next section presents the data related to the use of decision support systems and LOS indicators by city and county engineers. The last section presents the follow-up results and decision-making system developed by some city and county engineers.

3.1. Distress and Treatment Results and Analysis

Asphalt and Portland Cement Concrete Distresses

City and county engineers were asked to indicate the most common, common, and least common distresses existing. In addition, they were asked to report whether they collect pavement distress data or not. The distresses included in the questionnaire were based on the common distresses found in the literature. (The list of distresses included in this survey can be found in Figures 2 and 4.) Ten types of AC distresses were included while 14 types of PCC distresses were included. In addition, engineers were asked to add any other distresses that were not included.

Figures 2 and 3 show the AC pavement distress data collection results and the least common, common, and most common pavement distress type results for AC pavements, respectively.

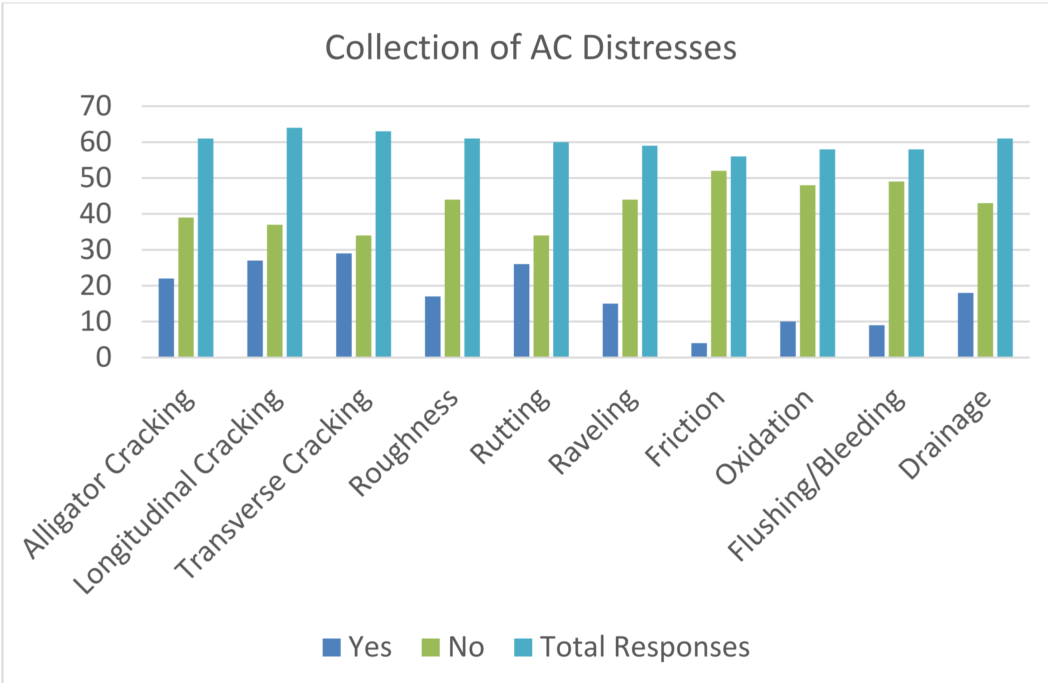

Figure 2. AC pavement distress type data collected

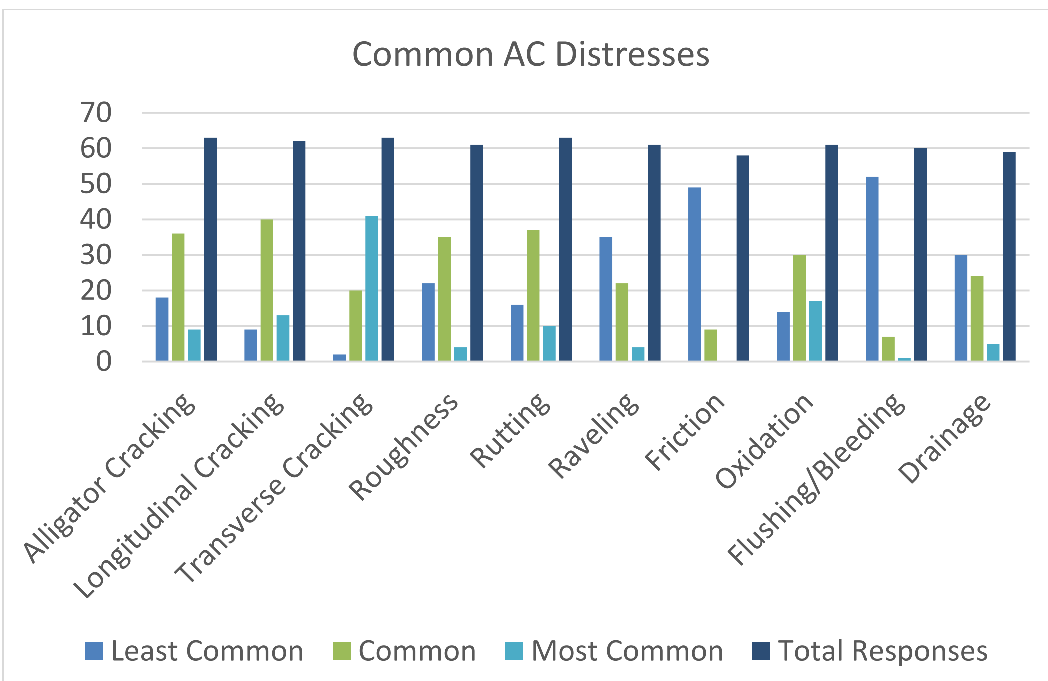

Figure 3. Least common, common, and most common AC pavement distresses

Respondents indicated that transverse cracking, longitudinal cracking, rutting, and then alligator cracking, have the most pavement distress data collected for AC pavements, while friction, flushing/bleeding, oxidation, and then roughness have the least (Figure 2). At the same time, the survey revealed that transverse cracking is the most common AC pavement distress while flushing/bleeding is the least common (Figure 3).

The gap between distress data collection and prevailing distress(es) appears by looking at transverse cracking. Sixty-one respondents indicated that transverse cracking is the most common or a common distress for AC pavement. However, only 29 respondents indicated that transverse cracking data is collected. Similarly, respondents indicated that rutting is a common pavement distress. However, more than 50 percent of the respondents do not collect rutting data.

Figures 4 and 5 show the PCC pavement distress data collection results and the least common, common, and most common pavement distress type results for PCC pavements, respectively.

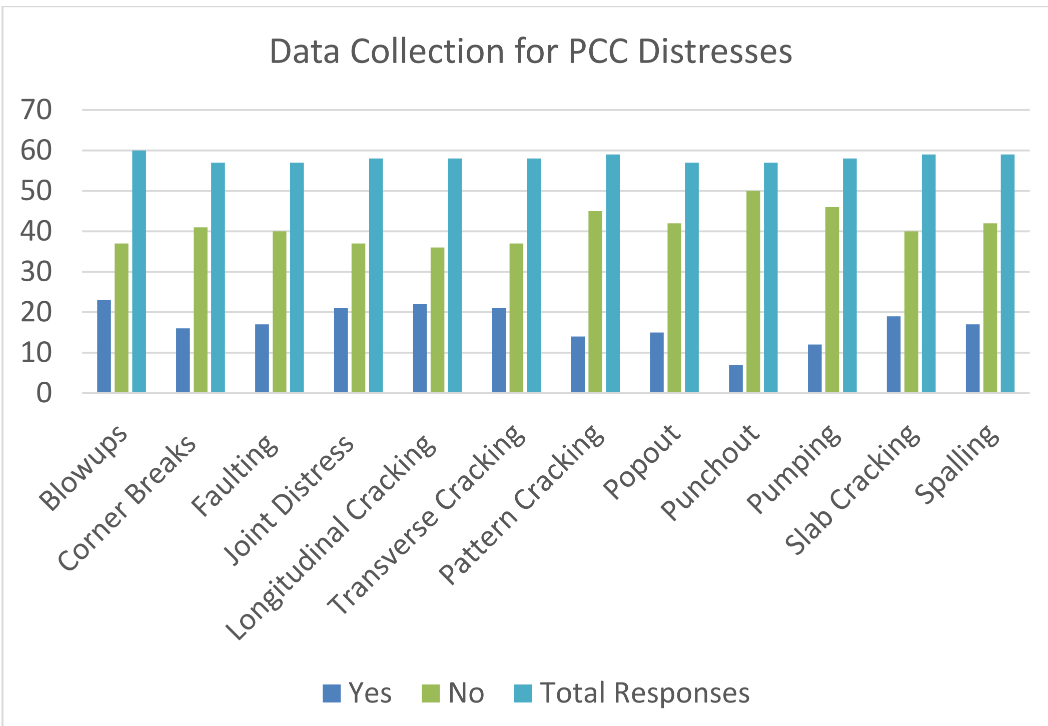

Figure 4. PCC pavement distress type data collected

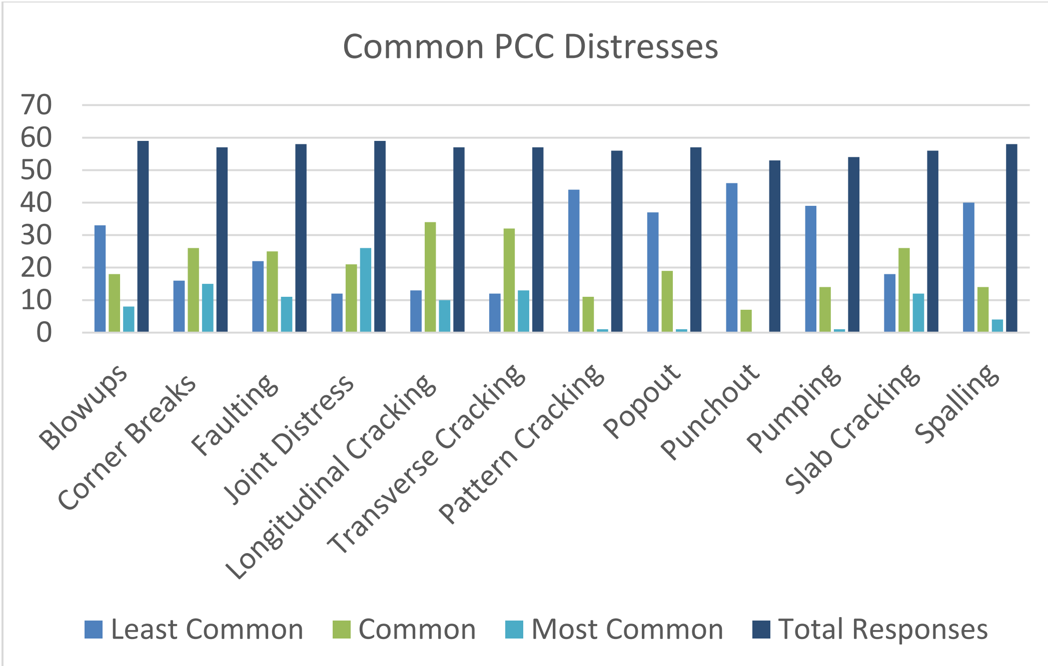

Figure 5. Least common, common, and most common PCC pavement distresses

Respondents indicated that blowups, longitudinal cracking, and then joint distress and transverse cracking have the most pavement distress data collected for PCC pavements, while punchouts, pumping, and then pattern cracking have the least (Figure 4). At the same time, respondents indicated that joint distress is the most common PCC pavement distress while punchouts are the least common.

Similar to AC pavement data collection methods, a gap appears between distress data collection and the existing common distresses for PCC pavements. For example, transverse cracking is a common PCC distress as indicated by respondents. However, less than 50 percent of the respondents collect transverse cracking distress data. The same problem exists for other types of distresses such as slab cracking and joint distress. Surprisingly, data collection for spalling, one of the least common pavement distresses, has nearly the same data collection results as joint distress.

The survey results show that pavement distress data collection is not proportionately relative to occurrence of pavement distress type.

Asphalt and Portland Cement Concrete Treatments

City and county engineers were asked to indicate the use of preservation, maintenance, and rehabilitation treatments for AC and PCC pavements. The purpose of these questions was to investigate the familiarity of different treatments to city and county engineers in the state. Accordingly, the proposed decision support system would consider the commonly used treatments as indicated by the engineers.

Figures 6 and 7 show the survey results for the usage of AC preservation and maintenance and AC rehabilitation treatments, respectively.

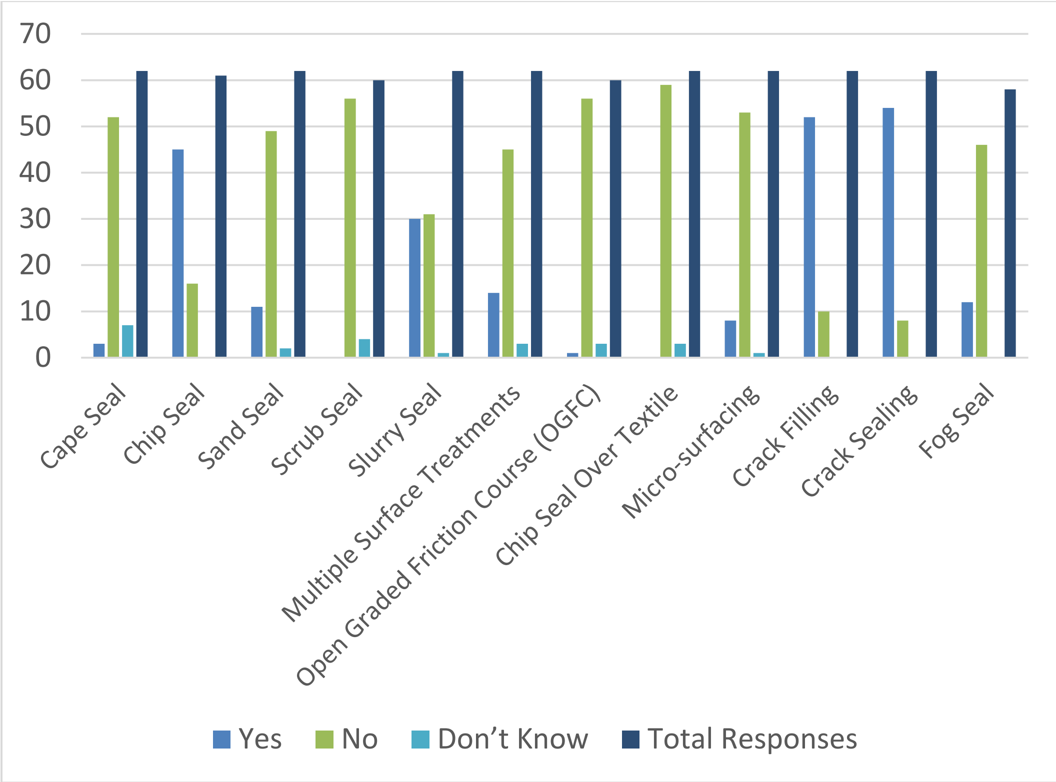

Figure 6. Application of AC preservation and maintenance treatments

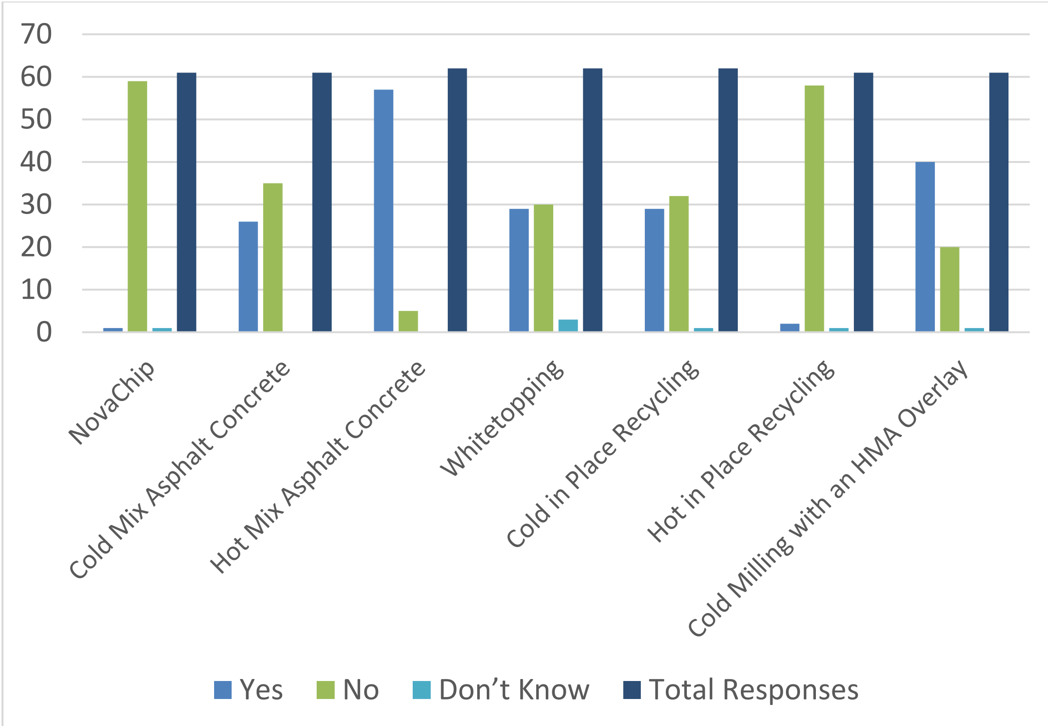

Figure 7. Application of AC rehabilitation treatments

Twelve AC preservation and maintenance treatments were included in the survey. Respondents indicated that crack filling, crack sealing, chip seal, and slurry seal are the most used AC pavement preservation and maintenance treatments applied (Figure 6). On the other hand, responses showed that chip seal over textile, OGFC, microsurfacing, fog seal, scrub seal, sand seal, and cape seal are not widely used by Iowa cities and counties.

Seven AC rehabilitation treatments were included in the survey. HMA overlay, cold milling with an HMA overlay, whitetopping, and cold in-place recycling are the AC rehabilitation treatments most applied. On the other hand, Novachip and hot in-place recycling are the least used by Iowa cities and counties.

Similarly, the same questions were asked to determine the common preservation and maintenance and rehabilitation treatments for PCC pavements. Figures 8 and 9 show the survey results for PCC preservation and maintenance and PCC rehabilitation treatment applications, respectively.

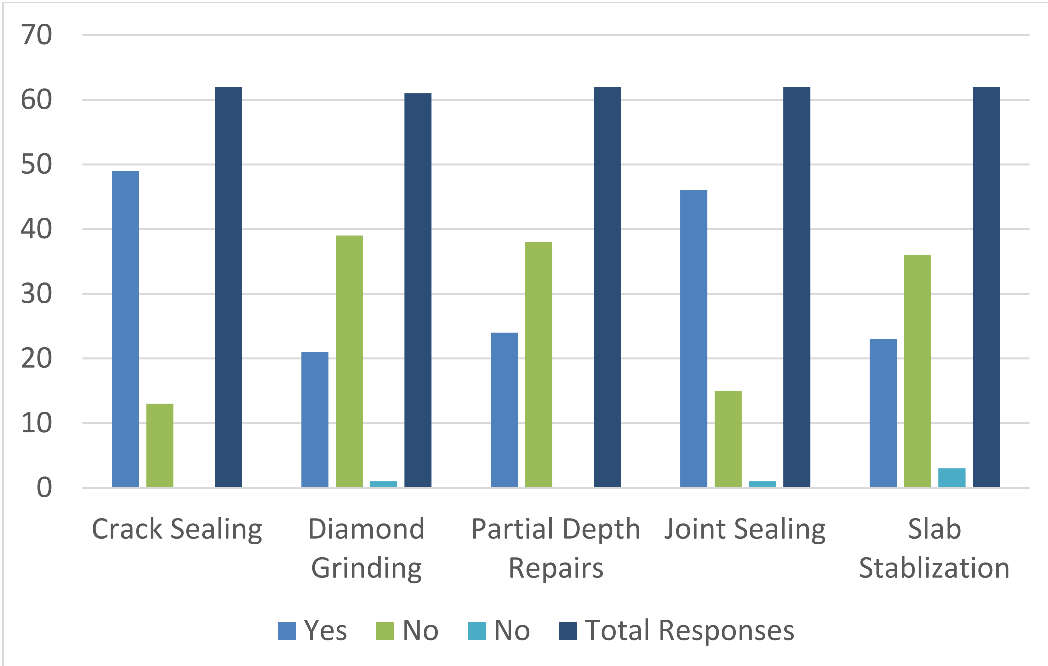

Figure 8. Application of PCC preservation and maintenance treatments

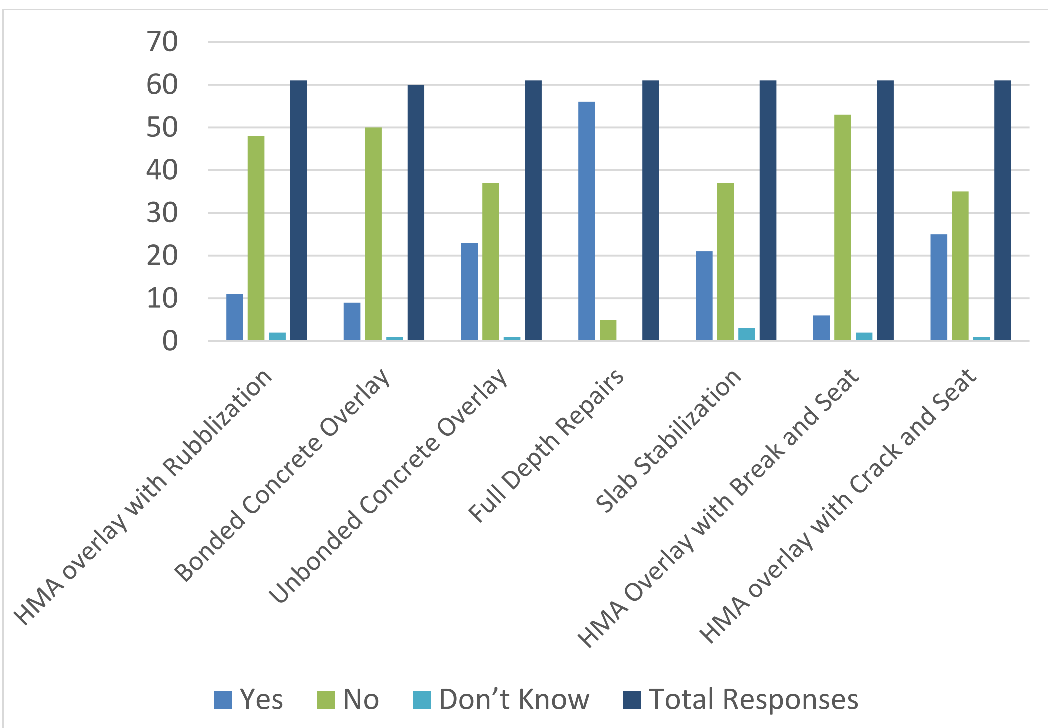

Figure 9. Application of PCC rehabilitation treatments

Five PCC preservation and maintenance treatments were included in the survey. Respondents indicated that crack sealing and joint sealing are the most used preservation and maintenance treatments for PCC pavements, while diamond grinding, partial-depth repairs, and slab stabilization are the least used.

Seven PCC rehabilitation treatments were included in the survey. Respondents indicated that full-depth repairs, HMA overlay with crack and seat, slab stabilization, and unbonded concrete overlay are the most used PCC pavement rehabilitation treatments, while HMA overlay with rubblization, bonded concrete overlay, and HMA overlay with break and seat are the least used. Note that full-depth repairs were included as a rehabilitation treatment while many DOTs consider them a maintenance treatment.

3.2. Use of Decision Support Systems

One of the essential objectives of this electronic survey was to investigate the existence and use of decision support systems or procedures adopted by Iowa city and county engineers. As a result, the respondents were asked to indicate if they use any decision-making procedure. In addition, respondents were asked to indicate if they use LOS indicators such as DI, IRI, rut depth, and so forth to determine the pavement condition.

The majority of the respondents indicated that they do not use any LOS while 21 percent of the respondents indicated that they use LOS indicators. In addition, 49 percent of the respondents indicated that they utilize a decision-making procedure to select the most appropriate treatment method. A follow-up questionnaire was conducted with these respondents and the results are summarized in the next and final section of this chapter.

3.3. LOS and Treatment Selection Follow-Up Question Results

A follow-up e-mail was sent to the survey respondents who indicated that they use LOS indicators or a treatment selection procedure. Respondents were categorized into three groups. The first group, of nine, included respondents who indicated that they use LOS indicators and a treatment selection procedure. Three of the nine replied to the follow-up e-mail and two of the three replied with relevant answers.

Clinton County indicated that PCI is used to prioritize pavement rehabilitation work. In addition, Clinton County depends on field evaluation to determine which preventive maintenance should be applied for old pavements. As for newer pavement, fog seal is applied every five to seven years, depending on the available funds.

Clinton County has developed a simple framework to select candidate roads for rehabilitation. The framework takes into consideration three factors: road age, condition based on PCI, and average daily traffic (ADT). Table 33 summarizes the scoring for the road age factor.

Table 33. Clinton County road age factor scoring values

Road age (years)	Score
More than 24	8
Between 24 and 19	4
Between 0 and 19	2
Equal to 0	4

Table 34 summarizes the Clinton County scoring for the road condition factor based on PCI value and the traffic volume factor based on ADT.

Table 34. Clinton County road condition factor and traffic volume factor scoring values

Road Condition (PCI value)	Score	Traffic Volume (ADT)	Score
$100 \geq PCI > 75$	6	$ADT > 2500$	8
$75 \geq PCI > 65$	8	$2500 \geq ADT > 2000$	6
$65 \geq PCI > 55$	12	$2000 \geq ADT > 1500$	4
$55 \geq PCI > 45$	16	$1500 \geq ADT > 1000$	2
$45 \geq PCI > 0$	20	$1000 \geq ADT > 500$	1
$PCI = 0$	25	$500 \geq ADT > 0$	0

The selection method is based on giving each factor a score and summing the scores of the three factors (road age score + road condition score + traffic volume score). A higher score represents a higher priority for rehabilitation.

Black Hawk County ranks road segments for full overlay or resurfacing needs. Black Hawk County developed its own decision-making process to rank road segments for full overlay or resurfacing. The decision-making process takes into consideration nine factors. Table 35 summarizes the list of factors taken into consideration and their weights.

Table 35. Black Hawk County criteria and their weights

Criteria	Weight
Structural condition	4
Surface condition	3
Traffic volume	3
Truck volume	3
Federal aid eligibility	2
Total project cost per mile	2
Nearest alternate paved route	1
Current total thickness	2
Age of current surface	1

Table 36 summarizes the Black Hawk County scores for structural and surface condition, traffic volume, and truck volume (before their associated weights in Table 35 are applied).

Table 36. Black Hawk County structural and surface condition, traffic volume, and truck volume scoring values

Structural and Surface Condition	Score	Traffic Volume (ADT)	Score	Truck Volume	Score
Excellent	1	0-400	1	Low	1
Good	2	410-690	2	Average	2
Fair	3	700-1250	3	High	3
Poor	4	1260-1750	4		
		>2000	5		

Table 37 summarizes the Black Hawk County scores for total project cost, nearest alternative route, and current total pavement thickness (before their associated weights in Table 35 are applied).

Table 37. Black Hawk County total project cost, nearest alternative route, and current total thickness scoring values

Total Project Cost Per Mile ($ per mile)	Score	Nearest Alternative Route (miles)	Score	Current Total Thickness (inches)	Score
>$250,000	1	<2	1	>10	1
$200,000-$250,000	2	2-4	2	8.5-10	2
$150,000-$200,000	3	4-6	3	6.5-8	3
<$150,000	4	None	4	3-6	4
				<2	5

Finally, Table 38 shows the Black Hawk County scoring values for the current surface age.

Table 38. Black Hawk County current surface age scoring values

Age (years)	Score
<10	1
10-15	2
16-25	3
>25	4

As shown in Table 35, Black Hawk County has an assigned weight for each factor, so the value for each factor is multiplied by its weight. The sum of all weighted scores is then used to indicate the priority for full overlay/resurfacing.

The second group, of 20, included survey respondents who indicated that they have a treatment selection framework. Three of the 20 replied to the follow-up e-mail.

The Montgomery County engineer depends on driving the roads on a semi-annual basis to capture the pavement network condition. Treatment selection is based on personal experience, funding available, and long-term schedule of maintenance.

The City of Marion relies on personal experience and judgment of the City engineers to select the appropriate treatments.

Butler County applies CIR with asphalt overlay in such a way that enables pavement resurfacing every 17 years. Crack sealing is applied every 5 to 6 years as preventive maintenance. However, strategies change as the cost of construction increases. If funding is not available, chip seal is used to protect the surface at age 17 +/- years, then a CIR with overlay should be applied 5 years later.

The third group, of 3, included survey respondents who indicated that they use LOS indicators. Two of the three replied to the follow-up e-mail.

The City of Davenport relies on the PCI provided by the Center for Transportation Research and Education (CTRE)/the Institute for Transportation (InTrans). The other respondent did not provide a relevant answer.

4. TREATMENT SELECTION FRAMEWORK FOR LOCAL AGENCIES

This chapter discusses development of the maintenance and rehabilitation treatment selection framework for local agencies. The framework is divided into three main phases, or steps, as outlined in Figure 10.

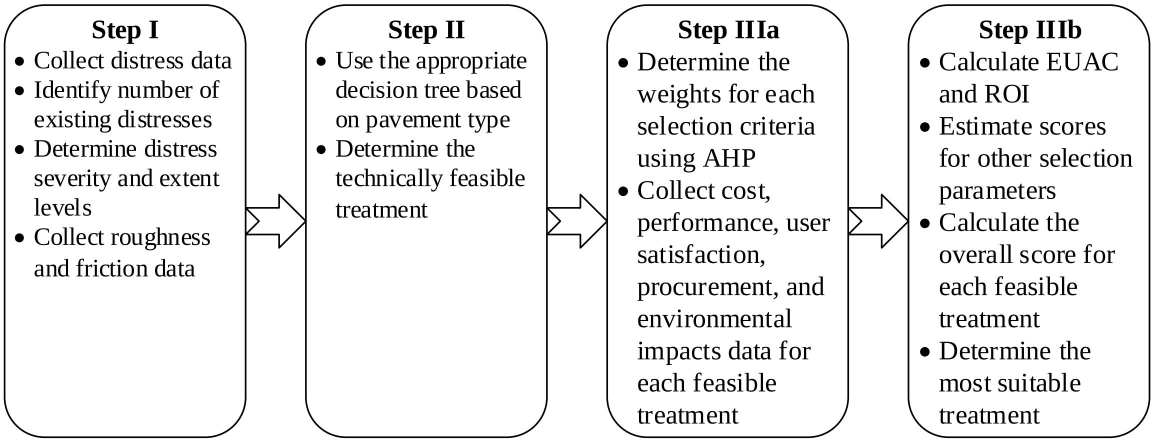

Figure 10. Treatment selection framework

The first step is to collect and identify the existing distresses for the pavement. This step includes collecting data about the number of existing distresses and the severity and extent level for each distress.

The second step includes a systematic process for determining the technically feasible treatments. These treatments are defined as the most appropriate treatments that can address the existing condition and extend the service life of the pavement. The outcome of the second step can be one or more technically feasible treatments.

The third and last step in the treatment selection framework involves a scoring method that considers different factors to determine the most effective treatment. This step can be divided into two sub-steps.

The first sub-step includes processes to determine the weights for each selection criteria using the analytic hierarchy process (AHP) and the collection of scoring data for different selection parameters. The second sub-step involves the calculation of cost selection parameters and determination of the overall score for each treatment. Different factors were included in the developed scoring method such as cost, ROI, treatment performance, user satisfaction, and environmental impacts.

The remainder of this chapter begins by presenting the recommended distress threshold values for both AC and PCC pavements. The next section presents the treatment selection decision trees for AC and PCC pavements, which are based on pavement condition classes for different types of pavements. These classes were determined based on the severity and extent levels for common distresses in Iowa. The treatment classification was used along with pavement roughness and friction to develop the systematic treatment selection decision trees. The next section presents assessment of the cost effectiveness for each feasible treatment. This is followed by the scoring method that was developed to select the most suitable treatment using the AHP. Finally, the last section in this chapter describes the Excel-based spreadsheet tool that was developed to automate the treatment selection framework.

4.1. Pavement Distress Threshold Values

The threshold values for each distress were determined based on other DOTs' practices and studies. For each distress, three levels of severity and extent are used to describe the pavement condition. The severity and extent levels are used to classify the pavement condition. In addition, the distress threshold values are an essential component for the decision trees.

Figure 11 shows the relationship between distress severity, extent, and treatment selection.

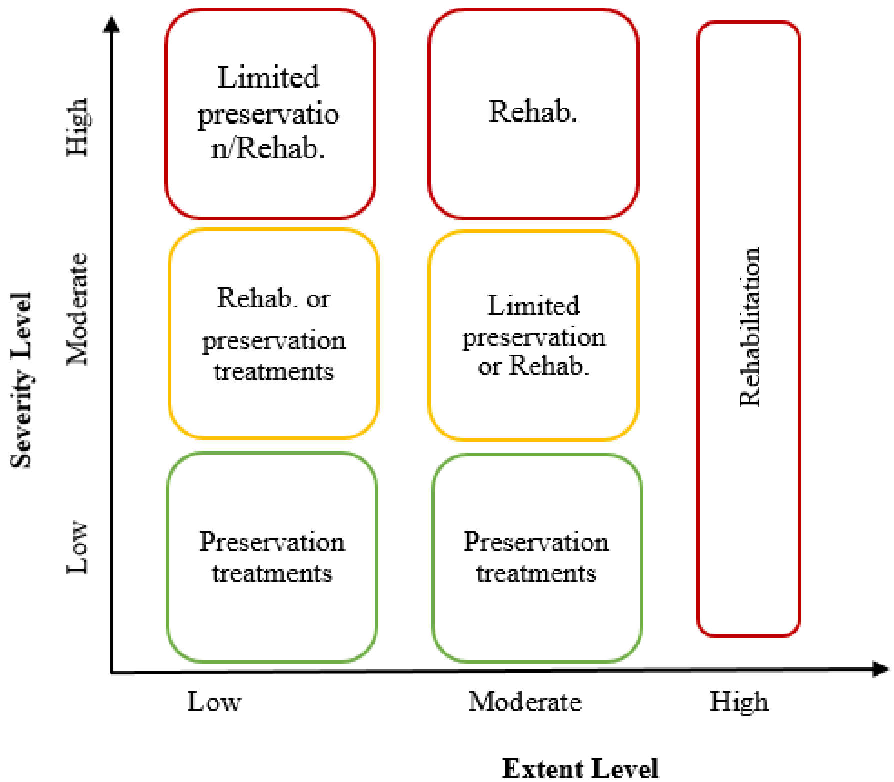

Figure 11. Relationship between distress extent and severity level leading to treatment strategy

The importance of using the extent and severity level for any distress can be exhibited in the following example. Crack filling or crack sealing may be recommended for a pavement showing low-severity longitudinal cracks. However, these two treatments will not be suitable if the extent level of the longitudinal cracks is too high. A rehabilitation treatment such as CIR should be recommended in this case.

Qualitative and quantitative measures were determined based on other DOTs' practices reported in the literature review. Also, a follow-up phone interview with some city and county engineers revealed that most local agencies depend on visual inspection.

Most of the local agencies also do not record quantified distress data for their pavements. Setting a quantitative threshold value for all distresses may be challenging for local agencies to use. Therefore, the three-level qualitative threshold value for distress severity and extent level was developed. Each qualitative threshold value is associated with a guiding quantitative measure, if applicable, to reduce subjectivity. It is more convenient for local agencies to use qualitative measures to describe the severity and extent level for each type of distress.

Note that the quantitative distress threshold values that follow can be changed to fit the agency's acceptable level of service. However, local agencies need to know that can lead to unexpected performance or early treatment failure. For example, applying a preventive maintenance treatment to a pavement with a poor structural condition would not yield any pavement performance improvements.

Asphalt Concrete Pavement Distress Threshold Values

Numerous distresses exist for AC pavements. The most common AC distresses for Iowa cities and counties are considered in this framework based on the survey results:

- Alligator cracking
- Longitudinal cracking
- Transverse cracking
- Rutting

For each type of distress, three severity levels and three extent levels are identified. The values for each threshold are summarized in Table 39.

Table 39. AC distress severity and extent levels

Distress	Severity level	Severity level threshold values	Extent level	Extent level threshold values
Alligator cracking	Low	Few connecting cracks	Low	1-9% of wheel path affected
	Moderate	Interconnected cracks forming pattern	Moderate	10-24% of wheel path affected
	High	Severely interconnected cracks	High	More than 25% of wheel path affected
Longitudinal cracking	Low	Mean width less than 6 mm (0.25 in.)	Low	Less than 500 m/km (2,640 ft/mile)
	Moderate	Mean width greater than or equal to 6 mm (0.25 in.) and less than 19 mm (0.75 in.)	Moderate	From 500 m/km (2,640 ft/mile) to 999 m/km (5,279 ft/mile)
	High	Mean width greater than or equal to 19 mm (0.75 in.)	High	Greater than or equal 1000 m/km (5,280 ft/mile)
Transverse cracking	Low	Mean width less than 6 mm (0.25 in.)	Low	Less than 150 m/km (792 ft/mile)
	Moderate	Mean width greater than or equal to 6 mm (0.25 in.) and less than 19 mm (0.75 in.)	Moderate	From 150 m/km (792 ft/mile) to 300 m/km (1,584 ft/mile)
	High	Mean width greater than or equal to 19 mm (0.75 in.)	High	Greater than or equal 300 m/km (1,584 ft/mile)
Rutting	Low	Mean depth less than 7 mm (0.27 in)	Low	1-9% of wheel path affected
	Moderate	Mean depth greater than or equal to 7 mm (0.27 in.) and less than 12 mm (0.5 in.)	Moderate	10-24% of wheel path affected
	High	Mean depth greater than or equal to 12 mm (0.5 in.)	High	More than 25% of wheel path affected

Many DOTs, such as Caltrans, IDOT, and NDOR (Cook et al. 2004, IDOT 2010, and NDOR 2002, respectively) do not use a quantitative measure to describe the severity level for alligator cracking. The severity levels of alligator cracking are not quantified since most local agencies do not collect distress severity data. However, qualitative measures for describing alligator cracking severity are provided for guidance and to reduce decision subjectivity.

Low-severity alligator cracking can be defined as a few connecting cracks in which cracks are not spalled or sealed. Moderate-severity alligator cracking is described as interconnected cracks forming a complete pattern. High-severity alligator cracking is severely interconnected spalled cracks forming a clear completing pattern (Miller and Billenger 2003). These severity level threshold values were adopted from the FHWA Distress Identification Manual for the Long-Term Pavement Performance Program (Miller and Billenger 2003).

The extent level of longitudinal cracking is calculated based on aggregating the number of cracks with different severity levels (Bektas et al. 2014). A low-severity crack counts as one crack while a medium- or moderate-severity crack counts as one and a half low-severity cracks. A high-severity crack counts as two low-severity cracks (Bektas et al. 2014).

Portland Cement Concrete Pavement Distress Threshold Values

Similar to AC distresses, common PCC distresses reported by Iowa cities and counties are considered in the framework that was developed:

- Longitudinal cracking
- Transverse cracking
- D-cracks
- Joint spalling
- Faulting

The severity and extent levels are each classified into three levels for the PCC distresses and Table 40 summarizes the threshold values.

Table 40. PCC distress severity and extent levels

Distress	Severity level	Severity level threshold values	Extent level	Extent level threshold values
Longitudinal cracking	Low	Mean width less than 3 mm (0.125 in.)	Low	Less than 125 m/km (660 ft/mile)
	Moderate	Mean width greater than or equal to 3 mm (0.125 in.) and less than 13 mm (0.5 in.)	Moderate	From 125 m/km (660 ft/mile) to 249 m/km (1,319 ft/mile)
	High	Mean width greater than or equal to 13 mm (0.5 in.)	High	Greater than or equal to 250 m/km (1,320 ft/mile)
Transverse cracking	Low	Mean width less than 3 mm (0.125 in.)	Low	Less than 75 m/km (396 ft/mile)
	Moderate	Mean width greater than or equal to 3 mm (0.125 in.) and less than 6 mm (0.25 in.)	Moderate	From 75 m/km (396 ft/mile) to 149 m/km (791 ft/mile)
	High	Mean width greater than or equal to 6 mm (0.25 in.)	High	Greater than or equal to 150 m/km (792 ft/mile)
D-cracking	Low	Tight with no loose pieces	Low	1-9% of slab affected
	Moderate	Well-defined cracks	Moderate	10-24% of slab affected
	High	Well-developed pattern	High	More than 25% of slab affected
Joint spalling	Low	Spalls less than 75 mm (3 in.)	Low	1-9% of slab affected
	Moderate	Spalls greater than or equal to 75 mm (3 in.) and less than 150 mm (6 in.)	Moderate	10-24% of slab affected
	High	Spall ≥ 150 mm (6 in.)	High	More than 25% of slab affected
Faulting	Low	Fault less than 5 mm (0.2 in.)	Low	1-9% of slab affected
	Moderate	Fault greater than or equal to 5 mm (0.2 in.) and less than 7.5 mm (0.3 in.)	Moderate	10-24% of slab affected
	High	Fault greater than or equal to 7.5 mm (0.3 in.)	High	More than 25% of slab affected

Extent level threshold values for PCC longitudinal and transverse cracking are calculated using the same methodology adopted for AC longitudinal and transverse cracking.

The extent level of longitudinal cracking is calculated based on aggregating the number of cracks with different severity levels (Bektas et al. 2014). A low-severity crack counts as one crack while a medium- or moderate-severity crack counts as one and a half low-severity cracks. A high-severity crack counts as two low-severity cracks (Bektas et al. 2014).

There are no quantified severity levels for D-cracks based on practices of other DOTs (IDOT 2014 Miller and Bellinger 2003, and SDDOT 2010). The severity levels of D-cracks are defined in qualitative measures (Miller and Billenger 2003). Low-severity D-cracking is defined as tight cracks with no loose or missing pieces while moderate-severity D-cracking is described as clearly defined cracks with loose small pieces. High-severity D-cracking is defined as a well-developed pattern of cracking associated with a significant amount of loose or missing material.

Again, local agencies may need to adjust these values to reflect their acceptable level of service. However, changing the threshold values for any type of distress may affect the treatment selection process. For example, joint resealing is a recommended treatment for addressing low-severity faulting problems. Increasing the low-severity threshold value to 7 mm instead of 5 mm will lead to unsuitability of joint resealing.

4.2. Treatment Selection Decision Trees

After determining distresses under consideration and their threshold values, a classification of pavement condition is developed. The purpose of pavement condition classification is to facilitate the treatment selection process. Pavement condition is classified into three classes. The first class indicates a highly deteriorated pavement that requires a rehabilitation treatment or heavy maintenance and repair treatment to address the existing condition(s). The second class indicates a moderately deteriorated pavement that may require a rehabilitation or maintenance treatment to address the existing distresses. Finally, the third class indicates a slightly deteriorated pavement. A third class pavement may not require immediate action. However, it is preferred to apply a maintenance or a preservation treatment to extend the pavement service life.

The treatment classification was used along with pavement roughness and friction to develop the systematic treatment selection decision trees. Treatment selection decision trees were developed for both AC and PCC pavements to help city and county engineers select the most appropriate treatment.

Pavements can be classified into three types according to the type of pavement surface. AC, PCC, and gravel-surfaced (unpaved roads) are the main three types of pavements. The scope of this study was limited to AC and PCC pavements only. There are some variations for each type of pavement. The Iowa DOT classifies its pavements into the types listed in Table 41.

Table 41. Iowa DOT pavement classifications for Interstate, highways, and primary roads

Type	Description
1	Portland cement concrete
2A	Continuously reinforced concrete with asphalt treated base
2B	Continuously reinforced concrete with cement treated base
3	Composite
3A	Composite built on old jointed Portland cement concrete pavement
3B	Composite built on continuously reinforced Portland cement concrete
4	Full-depth asphalt

For pavement maintenance purposes, classifying pavement type by surface type suits the purpose of selecting the appropriate treatment. Likewise, other DOTs such as IDOT (2010), MnDOT (2012a and 2012b), NDOR (2002), and SDDOT 2010 classify pavement into flexible and rigid pavements for maintenance purposes. The treatments included in the decision trees for flexible and rigid pavements are surface treatments. As a result, the classification of pavement types by surface type is beneficial for maintenance purposes. On the other hand, some distresses are related to a certain pavement type such as corner breaks for jointed PCC or punchouts for continuously reinforced concrete. However, these types of distresses were not reported as common distresses with the survey of Iowa cities and counties.

According to the FHWA Distress Identification Manual for the Long-Term Pavement Performance Program , distresses can be classified into three categories (Miller and Bellinger 2003):

- Distresses for AC surfaces
- Distresses for pavement with jointed plain Portland cement concrete pavement (JPCP)
- Distresses for pavements with continuously reinforced concrete pavement (CRCP)

However, one treatment selection decision tree was developed for rigid pavements and it should accommodate the two common types of rigid pavements. Longitudinal and transverse cracking are common distresses for both types of rigid pavements. Joint spalling can occur for both types of rigid pavements. Faulting is a distress related to jointed PCC only. The PCC treatment selection decision tree considers distresses for both types of rigid pavements.

The use of the treatment selection decision trees is intended only for local agencies. Local agencies manage city and county roads, which are characterized by low-volume traffic compared to Interstates and highways.

Treatment Selection Decision Tree for AC Pavements

AC pavement conditions are categorized into three classes. The severity and extent levels for each distress type in the different classes, as well as the potential treatments, are shown in Table 42.

Table 42. AC pavement condition classes and potential actions

Pavement Class	Distress Type	Severity Level	Extent Level	Potential Treatments: Global treatment	Potential Treatments: Localized Treatment
Class I	Alligator cracking	Any	Any	Thick HMA overlay, milling with overlay	Patching*
	Longitudinal cracking	High	Any	Whitetopping, CIR, milling with overlay and CIR	Patching*
	Transverse cracking	High to moderate	High		
	Rutting	High to moderate	Any	Thick HMA overlay, milling, milling with overlay and CIR	-
Class II	Longitudinal cracking	Moderate to low	High	Crack fill/seal, chip seal, microsurfacing or thin HMA overlay	-
	Transverse cracking	High to moderate	Moderate to low	Crack fill/seal, chip seal, sand seal, microsurfacing or thin HMA overlay	-
		low	high		
Class III	Longitudinal cracking	Moderate to low	Moderate to low	Do nothing, crack fill/seal, chip seal, microsurfacing	-
	Rutting	Low	Any	Do nothing, chip seal, microsurfacing, milling, milling and chip seal	-
	Transverse cracking	Low	Moderate to Low	Do nothing, crack fill/seal, chip seal, microsurfacing	-

*Treatment should only be used when distress extent level is low

The classifications are based on the following two factors:

- Severity and extent levels of existing distress
- Type of treatments that can address multiple distresses in the same class

The following example explains the concept behind classifying the pavements into three classes. Consider a pavement with high-severity alligator cracking and high-severity longitudinal cracking. This pavement is heavily deteriorated in a manner that maintenance treatments are not suitable to address the existing conditions. A rehabilitation treatment should be applied to address the existing condition. This pavement is classified as a Class I pavement. Other pavements with similar conditions should fall in the same class. The type of treatment recommended for each class is proportional to the level of deterioration. Major maintenance and rehabilitation treatments are recommended for Class I pavements while minor maintenance and preservation treatments are recommended for Classes II and III.

Potential treatments are recommended for each individual distress. Treatments recommend are divided into global and localized treatments. Global treatments are recommended when the distress is uniformly spread all over the pavement segment. On the other hand, patching is recommended when distresses are localized in one or more locations. It is necessary to separate global and local treatments from each other to present a fair financial comparison between treatments. For example, comparing patching to thick HMA overlay leads to an unfair comparison.

Class I pavement should have at least one of the following distresses:

- Alligator cracking
- Longitudinal cracking
- Transverse cracking
- Rutting

These distresses are associated with the severity and extent levels listed in Table 42.

Distresses in Class I are associated with high to moderate severity levels and should be addressed using a rehabilitation treatment. All pavements exhibiting alligator cracking should fall into Class I. The existence of alligator cracking indicates a problem in the pavement structural system itself and maintenance treatments should not be a potential action. Similarly, the existing high-severity longitudinal cracking, high/moderate transverse cracking, and high/moderate rutting will disqualify the pavement from any maintenance treatment. In addition, Class I pavements should show some structural deficiency, which means a pavement structure enhancement is needed. The following treatments are recommended for Class I pavements:

- CIR
- Thick HMA overlay
- Whitetopping
- Patching

These treatments were selected based on the most widely used rehabilitation and major maintenance treatments in Iowa.

Class II contains longitudinal and transverse cracking associated with severity and extent levels that can be addressed using a maintenance/preservation treatment. Longitudinal and transverse cracking are the distresses considered for Class II pavements. The distress severity and extent levels are described in Table 42. The following treatments are used to address Class II pavements:

- Crack fill
- Crack seal
- Chip seal

- Microsurfacing
- Thin HMA overlay

Class III contains transverse cracking, longitudinal cracking, and rutting. The severity and extent level for each distress ranges from low to moderate. The treatments recommended for Class III pavements are similar to the treatments recommended for Class II pavements. However, a do nothing alternative can be feasible for Class III pavements. In addition, thin HMA overlays are not utilized for Class III pavements.

In many cases, pavement segments exhibit multiple distresses. The use of treatment decision matrices to select the recommended treatment therefore may be a challenging task. A decision tree for each pavement class was developed instead and follows.

Most of the treatments used in the treatment selection decision trees for AC pavements are suitable for typical city and county low and high traffic volume roads. For example, crack filling, crack sealing, chip seal, and microsurfacing are feasible treatments for low- and high-volume roads (IDOT 2010). However, CIR is not recommended for roads with ADT more than 10,000 vehicles per day (vpd) (IDOT 2010). Whitetopping is considered a suitable treatment for low to high traffic volume roads (Maher et al. 2005).

Pavement class needs to be determined to choose the appropriate decision tree. Pavement class is determined based on the worst existing distress. For example, a pavement that exhibits alligator cracking and low-severity transverse cracking is considered a Class I pavement. After determining the pavement class, one of the three decision trees can be used to obtain the technically feasible treatments.

Figure 12 shows the treatment selection decision tree developed for AC Class I pavements.

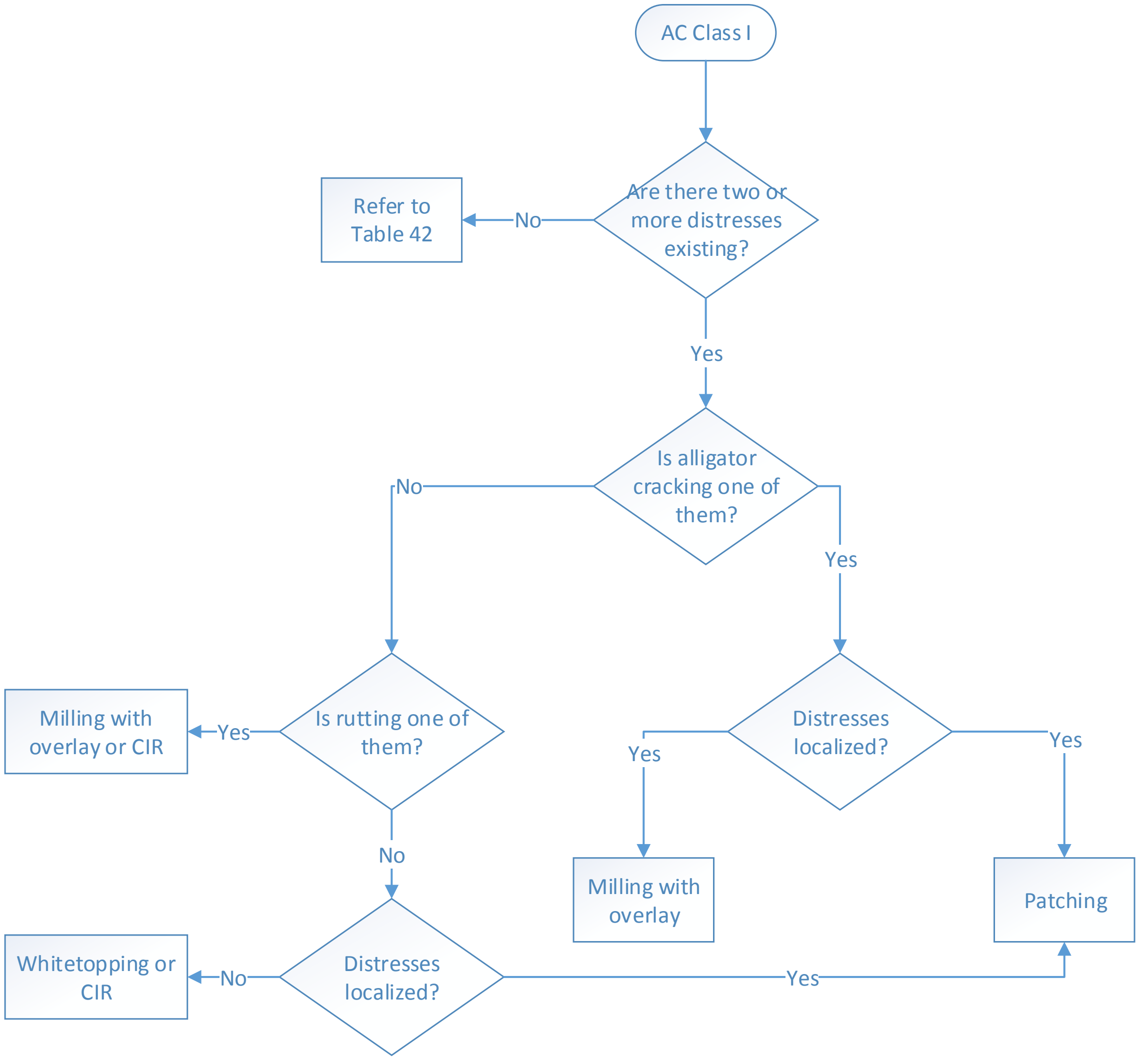

Figure 12. AC Class I pavement treatment selection decision tree

The decision tree starts with asking the user whether there are two or more existing distresses. If the answer is No, the user should refer to Table 42 . The user can then use the table to easily match between the recommended treatments for the distress severity and extent level and choose the appropriate treatment for that single existing distress type.

When more than two distresses exist, the decision tree asks the user whether alligator cracking is one of the existing distresses. If alligator cracking exists, patching should be a potential action if the distresses are localized. If distresses are distributed all over the pavement segment, milling with overlay should be the recommended action.

In other cases, alligator cracking will not exist among the existing distresses. In this case, the decision tree verifies if rutting is one of the existing distresses. If the pavement segment exhibits rutting, milling with overlay or CIR can be recommended as potential actions. If rutting and alligator cracking do not exist, patching can be recommended for localized treatments. If distresses are not localized, whitetopping or CIR will be the recommended actions.

Figure 13 shows the treatment selection decision tree for AC Class II pavements.

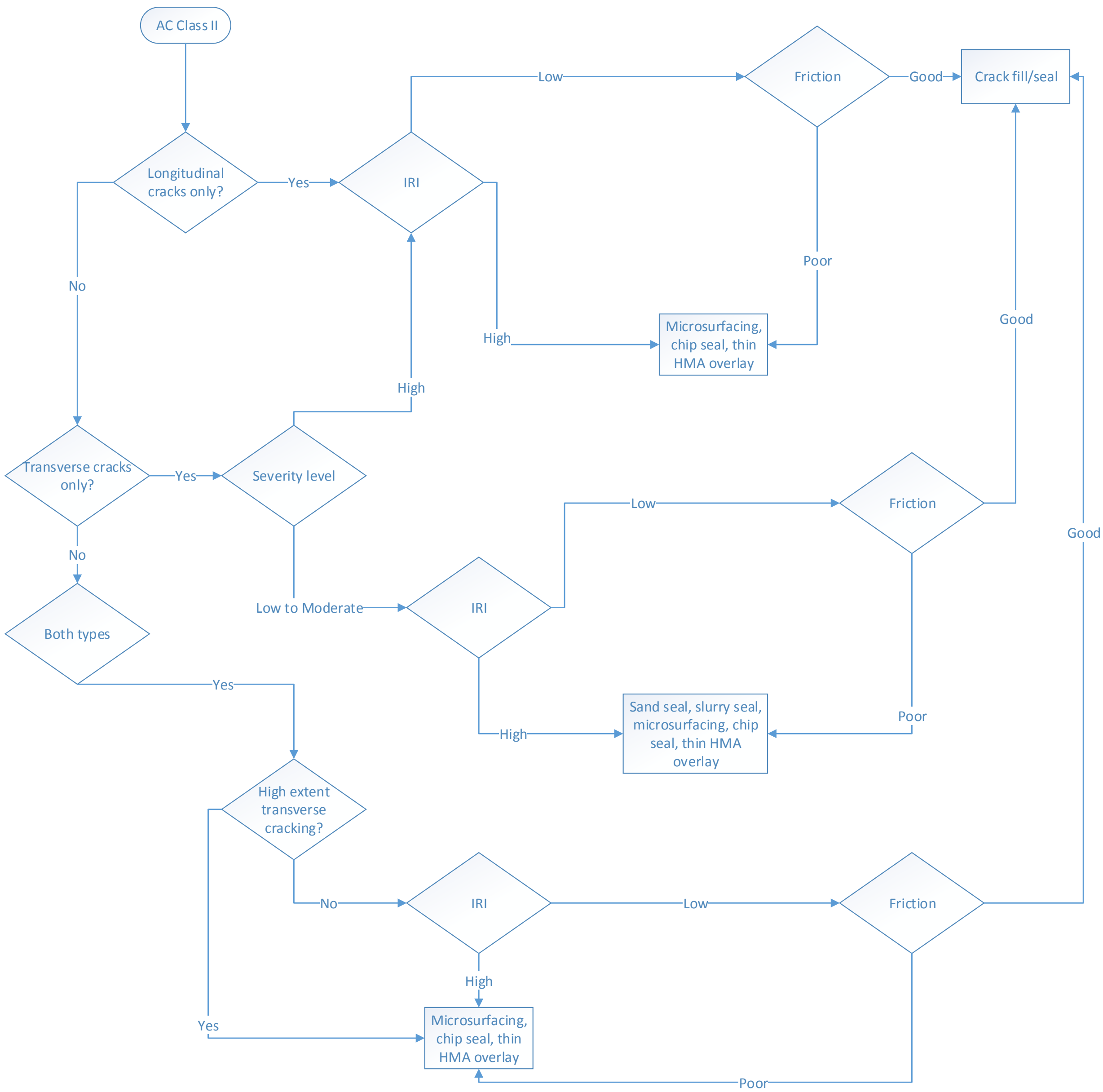

Figure 13. AC Class II pavement treatment selection decision tree

The AC Class II decision tree starts with determining whether longitudinal cracks are the only existing distress or not. If longitudinal cracks are the only existing distress, other decision parameters will be examined. These decision parameters are roughness and friction. Fundamentally, crack sealing or crack filling should not be recommended for pavements with the following criteria:

- High roughness
- Poor friction

If roughness or friction problems exist, the following treatments will be recommended:

- Mirosurfacing
- Chip seal
- Thin HMA overlay

The second scenario for AC Class II pavements is the existence of transverse cracks only. In that case, the severity level of transverse cracks should be considered along with roughness, and friction. Sand seal and slurry seal are not recommended for high-severity cracks.

The last possible scenario for AC Class II pavements is the existence of both longitudinal and transverse cracks. The aforementioned decision parameters are examined to select a set of technically feasible treatments.

Finally, an AC pavement may fall into the third class. AC Class III pavements could exist because of longitudinal cracking or rutting. Figure 14 shows the treatment selection decision tree for AC Class III pavements.

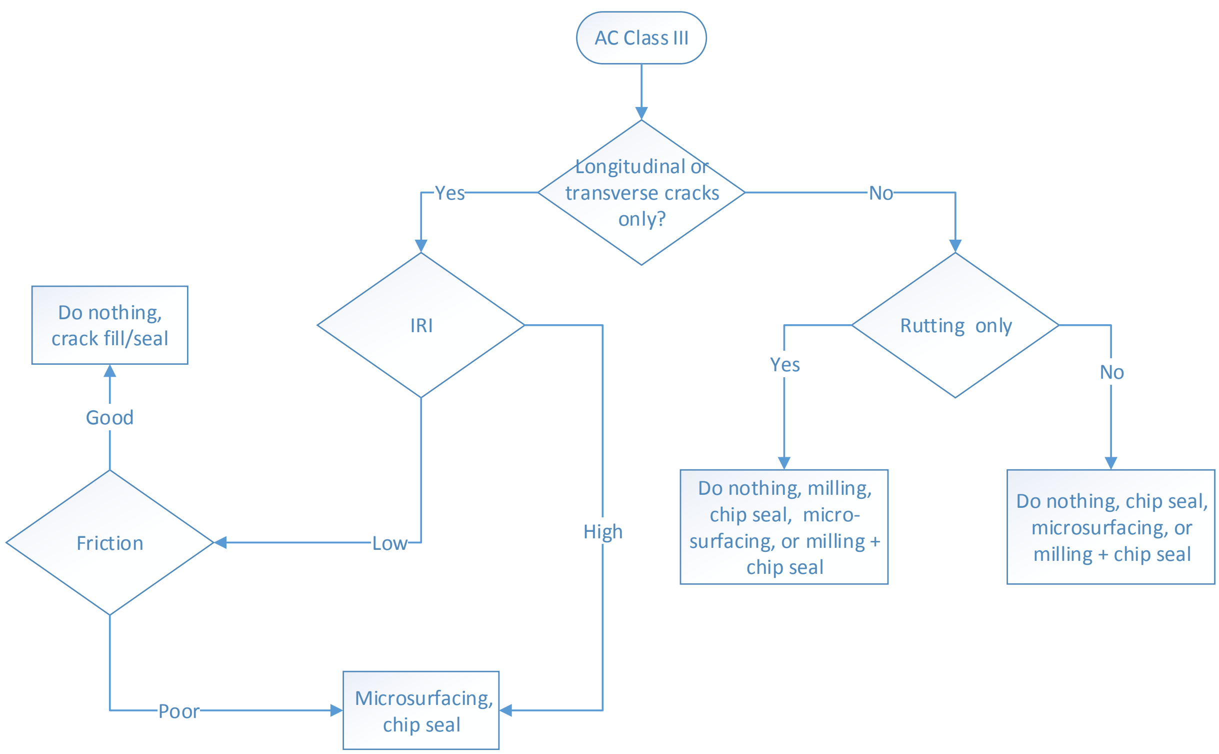

Figure 14. AC Class III pavement treatment selection decision tree

Similar to AC Class II, AC Class III pavements should be investigated to determine whether one or both distresses (longitudinal cracking and/or rutting) exist. If longitudinal cracking is the only distress that exists, a further investigation of pavement roughness should be done. If rutting or both types of distresses exist, pavement roughness will not be considered, as all feasible treatments restore pavement roughness.

Treatment Selection Decision Tree for PCC Pavements

Similar to AC pavements, PCC pavement conditions are categorized into three classes. The severity and extent levels for each distress type in the different classes, as well as the potential treatments, are listed in Table 43.

Table 43. PCC pavement condition classes

				Potential Treatments	
Category	**Distress Type**	**Severity Level**	**Extent Level**	**Global Treatment**	**Localized Treatment**
Class I	Longitudinal cracking	High to moderate	High to moderate	Thick HMA overlay with crack and seat or thick HMA overlay with rubblization	Full-depth repair
	Transverse cracking	High to moderate	High to moderate	Thick HMA overlay with crack and seat or thick HMA overlay with rubblization	Full-depth repair, slab replacement
	D-cracking	High	Any	-	Full-depth repair
	Joint spalling	High to moderate	Any	-	Full-depth repair
Class II	Longitudinal cracking	Low	High	Crack sealing	Full-depth repair
		High to moderate	Low		
	Transverse cracking	Low	High	Crack sealing	Full-depth repair
		High to moderate	Low		
	D-cracking	Moderate to low	Any	-	Partial-depth repair
	Faulting (JPCP)	High	Any	Diamond grinding*	-
Class III	Longitudinal cracking	Low	Low to moderate	Do noting or crack sealing	-
	Transverse cracking	Low	Low to moderate	Do nothing or crack sealing	-
	Joint spalling	Low	Any	Do nothing or joint resealing	-
	Faulting (JPCP)	Low to moderate	Any	Do nothing, diamond grinding*, or joint resealing	-

*Diamond grinding should be used in conjunction with a load transfer restoration technique

PCC Class I pavement consists of four different distress types: longitudinal cracking, transverse cracking, D-cracking, and joint spalling. The recommended treatments for PCC Class I pavements vary according to the type of existing distresses. Pavements that exhibit high-severity longitudinal, transverse, D-cracking, and joint spalling are not eligible for maintenance and preservation treatments. The following rehabilitation treatments are used to address PCC Class I pavements:

- Full-depth repairs
- HMA overlay with crack and seat
- HMA overlay with rubblization
- Slab replacement

Similarly, PCC Class II pavement is classified based on the existence of four different types of distresses. The severity and extent levels for distresses in PCC Class II are lower than the severity and extent levels in PCC Class I. Several treatments can be employed to address PCC Class II distresses:

- Crack sealing
- Diamond grinding
- Full-depth repair
- Partial-depth repair
- HMA overlay

PCC Class II pavements are moderately deteriorated. A maintenance or a rehabilitation treatment should be effective enough to address the existing distresses. For example, a low-severity crack can be addressed using crack sealing. Faulting is a distress that occurs for JPCP only.

Finally, distresses with low to moderate severity and extent levels are grouped in PCC Class III. PCC Class III pavements have one or more existing distresses associated with the specific severity and extent levels shown in Table 43. PCC Class III pavements do not require immediate treatment application given that pavements are slightly deteriorated. However, treatments such as crack seal sealing and joint resealing can be utilized to address existing conditions.

Most of the treatments used in the treatment selection decision tree for PCC pavements are not affected by the traffic volumes. For example, the performance of crack sealing, joint resealing, diamond grinding, full-depth repairs, and partial-depth repairs is not affected by the traffic volume (IDOT 2010). (Diamond grinding can remove existing faulting but faulting can occur again under heavy traffic loading.)

Figure 15 shows the treatment selection decision tree for PCC Class I pavements.

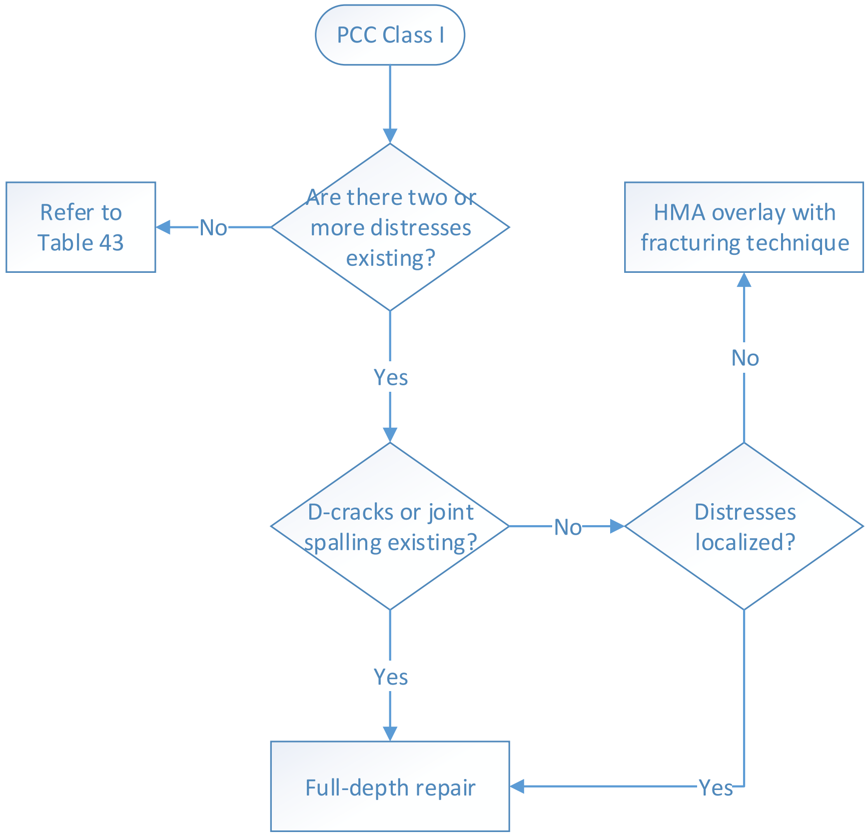

Figure 15. PCC Class I pavement treatment selection decision tree

The decision tree starts with determining whether there are less than two existing distress types. If the number of distress types is less than two, the decision maker should refer to Table 43 to select the appropriate treatment.

When more than two distress types exist, the user needs to determine whether the distresses include D-cracks or joint spalling. Full-depth repair is recommended if D-cracks or joint spalling exist.

If the pavement segment only exhibits longitudinal and transverse cracks, the decision tree asks whether the distresses are localized. If distresses are localized, full-depth repair is recommended to address the existing conditions. If the distresses are not localized, HMA overlay with break and seat or rubblization is recommended to address the existing conditions.

Roughness and friction are not considered for PCC Class I pavements since all potential treatments used in this decision tree should restore pavement roughness and friction.

Figure 16 shows the treatment selection decision tree for pavements classified as PCC Class II pavements.

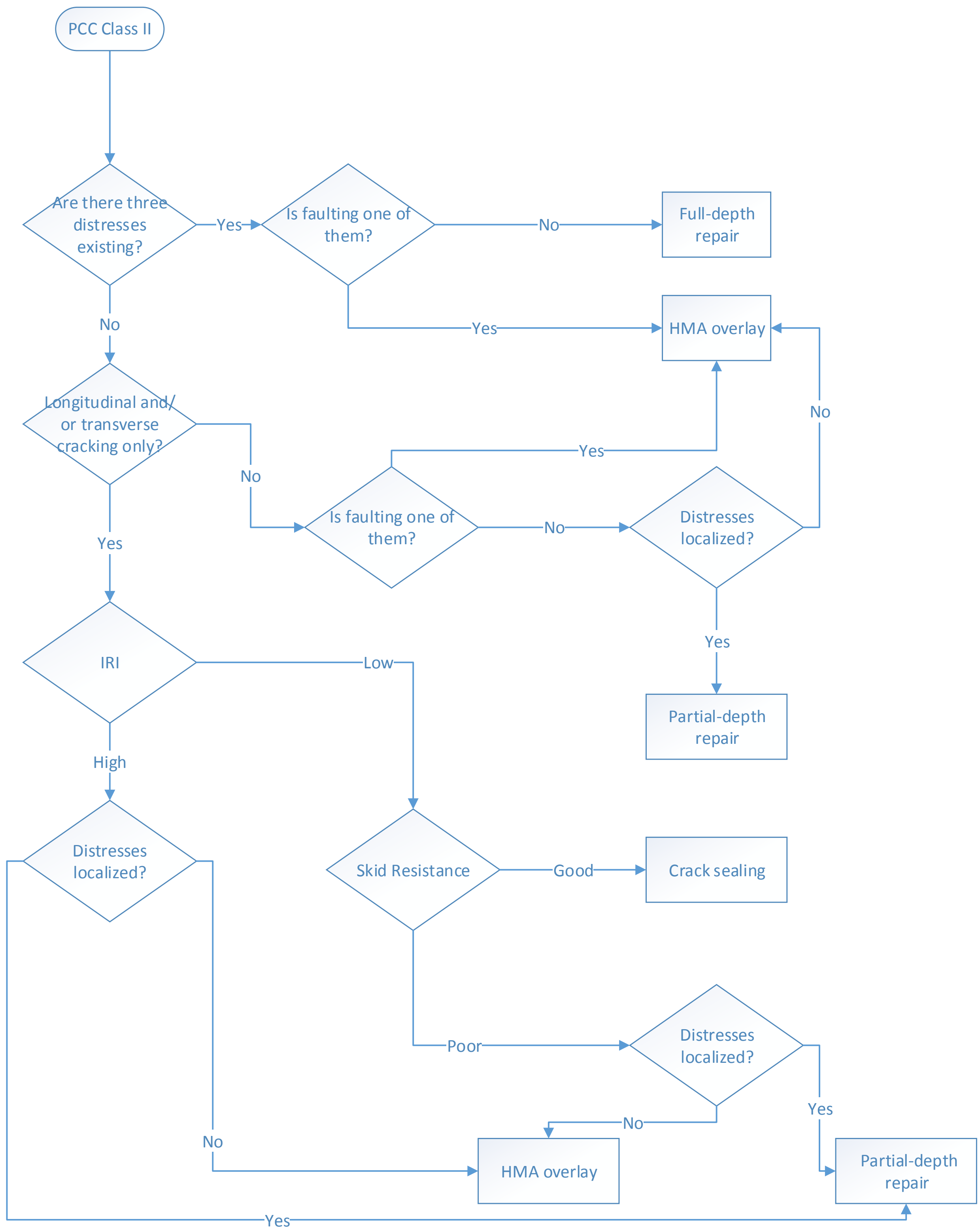

Figure 16. PCC Class II pavement treatment selection decision tree

First, the decision tree checks whether three distress types exist. If there are three or more distress types that exist, the user should check whether faulting is one of them or not. If faulting is one the existing distresses, HMA overlay can be used to address the existing conditions. If D-cracks exist along with longitudinal and transverse cracks, full-depth repairs are required to address the existing D-cracks.

For pavements where longitudinal and transverse cracks are the only existing distresses, skid resistance and roughness need to be considered. Roughness and skid resistance should be checked before applying crack sealing. Crack sealing is not recommended for pavements with high roughness or poor skid resistance. In addition, distress distribution among the pavement segment is considered. For localized distresses, partial or full-depth repairs are recommended. For distresses that are not localized, crack sealing and HMA overlay are recommended.

Finally, Figure 17 shows the treatment selection decision tree for PCC Class III pavements.

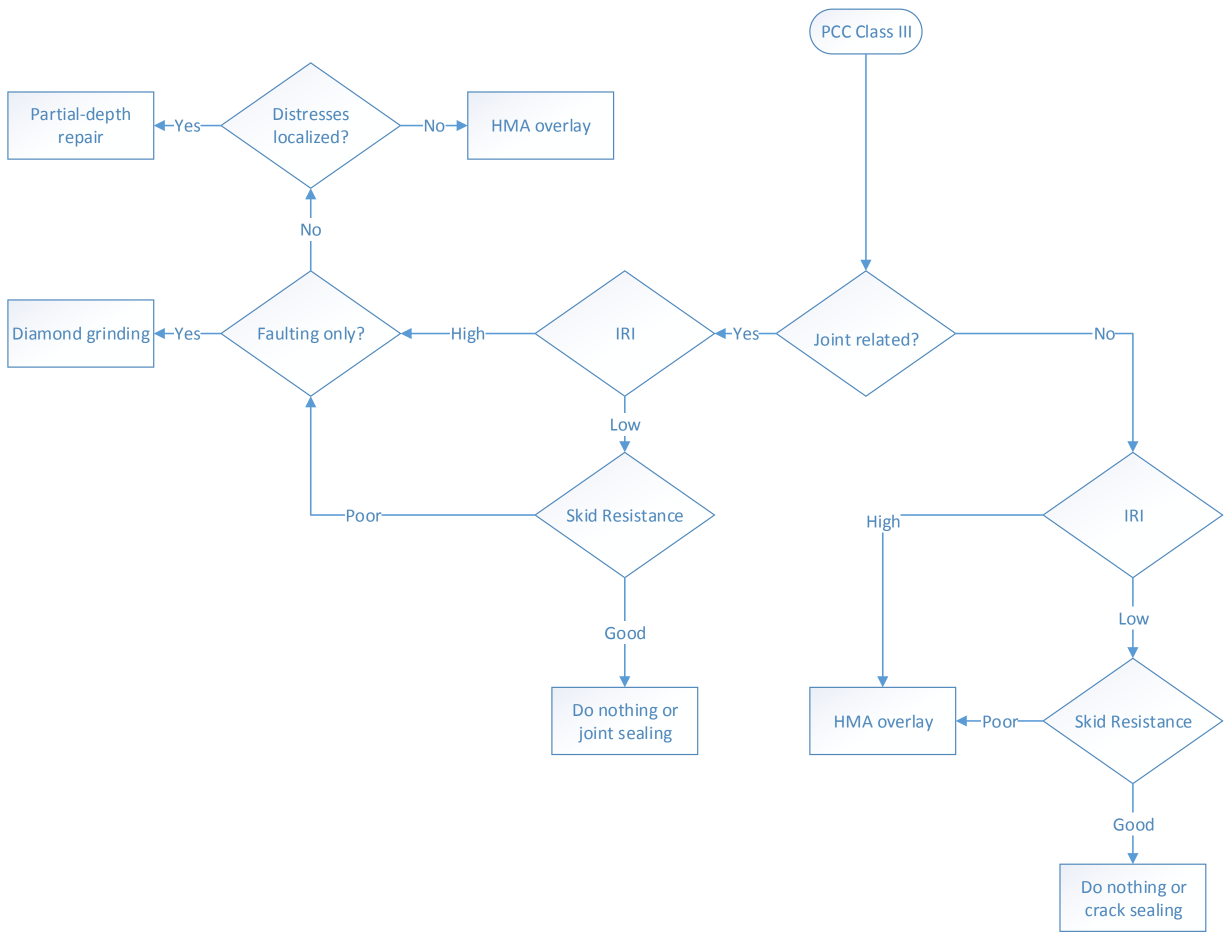

Figure 17. PCC Class III pavement treatment selection decision tree

PCC Class III pavements can be treated using crack sealing, joint resealing, and diamond grinding. In some cases, the local agency may choose to do nothing as the pavement condition does not require immediate action. To determine whether crack sealing or joint resealing should be used, it is essential to investigate whether the distress is joint-related or not.

Some PCC Class III pavements may have skid resistance or roughness problems. HMA overlay can be used to address these problems.

Faulting is addressed by diamond grinding. Load transfer restoration should be used in conjunction with diamond grinding. Distress distribution over the pavement segment is considered with partial-depth repair recommended for localized distresses while HMA overlay is recommended for non-localized distresses.

4.3. Assessment of Treatment Cost Effectiveness

The next stage after determining the set of feasible treatments is to evaluate the cost effectiveness for each treatment. The assessment of treatment cost effectiveness is based on the calculation of the EUAC given in equation 1,

$$\mathrm{EUAC} = \mathrm{P} \times \frac{i\,(1+i)^{n}}{(1+i)^{n} - 1} \qquad \textbf{(1)}$$

where P is the total treatment cost at the year of application, i is the discount rate, and n is the extended pavement service life. The total cost of the treatment should include construction, agency, and user costs, and any other costs that may affect the assessment. City and County engineers should use their engineering judgment or their own collected cost data to accurately assess the treatment cost effectiveness.

Using EUAC to assess the cost effectiveness of different treatments presents a fair comparison between different alternatives since the expected service life for each treatment is different. Note that the use of net present value (NPV) to compare the cost effectiveness of various treatments has showed major problems in determining the analysis period for two or more treatments (Pittenger et al. 2011). The analysis period may be as follows:

- Shortest service life among treatments
- Longest service life among treatments
- Least common multiple of the life of the treatments
- Standard analysis period
- Infinite long (Pittenger et al. 2011)

Setting the analysis period to the shortest or longest treatment life will lead to an unfair comparison (Pittenger et al. 2011). There is no consensus on which analysis period method should lead to a fair comparison (Pittenger et al. 2011). The EUAC model developed by Pittenger et al. (2011) has a termination feature that considers the rehabilitation intrusion after preservation or maintenance application. The termination concept implies that the expected service life of a preservation/maintenance treatment should be truncated when the timing of rehabilitation treatment is known. This concept should be applied when calculating the EUAC for any preservation/maintenance alternative.

The treatment construction cost should vary according to location, physical conditions (traffic control and safety measures), and so forth. Many studies have reported the cost of different treatments. These studies were reported in the literature review so that cities and counties can use those treatment cost figures as a starting point for evaluating treatment cost effectiveness. However, the use of cost data from other states should be done cautiously.

As part of this project, efforts went into estimating the unit cost for different treatments in Iowa using historical data. The Iowa DOT has been collaborating by providing the historical cost data for different treatment projects. The historical data provided by the Iowa DOT contains cost data for maintenance and rehabilitation projects since 1999.

The database developed by the Iowa DOT contains information about project location, project type, tasks for each project, item costs, physical length, and so forth. The location of the projects is given using a longitude and latitude and/or beginning milepost and ending milepost.

For example, an HMA resurfacing project was let on January 2012 with an award amount of approximately $1.2 million. The length of the project was four miles and the project was located in Cass County. There are 14 items recorded for this project along with their unit costs and quantities. The location of the project was recorded using the longitude and latitude, 95.11 and 41.50, respectively, for the project's midpoint. Note that the absolute values of the projects' longitude and latitude were recorded in this case, while the longitude and latitude for some projects was not. The length for some projects was not recorded either.

The estimation of the unit cost of different treatments based on the historical data collected by the Iowa DOT was not feasible. The unit cost estimation for different treatments was not developed because the Iowa DOT did not collect the number of lanes for each project. The length recorded in the database is the physical length of the project, without reflecting the number of lanes or pavement lane-miles.

In addition, the treatment projects database is not compatible with the Pavement Management Information System (PMIS) in terms of units of measurement and road system numbering methods.

For example, the PMIS uses metric units while the treatment projects database uses English (US customary/standard) units.

The PMIS uses three classes to determine the road system:

- Interstates
- US highways
- Iowa roads

While, the treatment projects databases road numbering system is more complex with seven different road systems defined as follows:

- Interstate
- Primary
- Farm-to-market
- Other state roads
- Local secondary roads and others
- Recreational trails
- Non-highway roads

Discount rate is another essential piece of information needed to calculate EUAC for any treatment. A discount rate of 3.5 percent is recommended to calculate the EUAC based on other DOTs' practices and studies. But, the discount rate used to calculate the EUAC may vary from one agency to another as evidenced by the following studies.

Peshkin et al. (2004) developed several case studies to validate a methodology that finds the optimal timing of pavement maintenance applications. The case studies included projects from Arizona, Kansas, Michigan, and North Carolina. A discount rate of 4.0 percent was used for the Arizona, Michigan, and North Carolina case studies, while the Kansas DOT (KDOT) uses a discount rate of 2.0 percent.

Likewise, Villacres (2005) developed lifecycle cost studies using actual cost data from Iowa, Kansas, and Ohio. The Ohio DOT (ODOT) used a discount rate of 5.0 percent, while 3.5 percent was used for Kansas and 4.0 percent was used for Iowa.

These studies show that the discount rate can vary according to agency preference and experience, with a discount rate range of 2.0 to 5.0 percent.

After calculating the EUAC for each alternative, the ROI can be calculated. Cambridge Systematics (2008) developed a study that focuses on integrating various factors into ROI evaluation:

- Lifecycle costs
- Travel-time reliability
- Economic growth
- Public-private partnership

Lifecycle cost analysis (LCCA) is more relevant when selecting between different maintenance or rehabilitation alternatives at a local agency level. As for local agencies, preservation or maintenance treatments are applied to delay the need for rehabilitation treatments. The ROI of preservation or maintenance treatments can be estimated by calculating how much the local agency saved by delaying the road rehabilitation or reconstruction compared to a do nothing alternative. A decision based on the EUAC and ROI can be made by ranking the alternatives that have the highest ROI.

4.4. Feasible Treatment Selection Scoring System

In some cases, agencies would like to investigate other factors that are not related to the treatment costs. Table 44 shows the criteria included in the scoring system that was developed to select the most appropriate treatment.

Table 44. Feasible treatment selection factors

Category	Selection Factors
Performance	Pavement Structure Improvement
	Performance Under Heavy Traffic Loading
	Performance Under Average Daily Traffic
User Satisfaction	Facility Downtime, Road Closure, or Traffic Disruption
	Impact on Roughness
	Impact on Friction
	Tire/Road Noise
Procurement and Contracts	Availability of Qualified Contractors
	Availability of Quality Material
Environmental Sustainability	Negative Environmental Impact

Using EUAC or treatment initial cost as the only basis of comparison to choose the most appropriate treatment may lead to an uninformed decision. Treatment cost is therefore not the only factor that affects the treatment selection process, especially when the selection process is performed by a city or county agency.

Treatment performance, user satisfaction, procurement and contracts, and environmental sustainability are other factors that should be considered when selecting a treatment. As a result, a proper scoring method was developed to help in selecting the most appropriate treatment.

The selection factors to consider were determined based on the treatment selection framework developed by Hicks et al. (2000) and Caltrans (2003). In addition, Iowa City and County engineers' input (through phone and e-mail interviews) was integrated into the scoring system.

Performance Factors

The first category considered in the scoring process is the performance category. This category includes the following factors:

- Pavement structure improvement
- Performance under heavy traffic loading
- Performance under average daily traffic

Pavement structure improvement is an essential factor in the decision-making process. For example, HMA overlay with rubblization would impact the pavement structure positively compared to HMA overlay with no fracturing technique. Feasible treatments would have different performance levels under heavy or regular daily traffic. Treatments that enhance the structural capacity for pavements will be preferred for roads with heavy and frequent traffic loading.

User Satisfaction Factors

User satisfaction is the second selection category in the scoring process. User satisfaction consists includes the following factors:

- Facility downtime, road closure, or traffic disruption
- Impact on roughness
- Impact on friction
- Tire/road noise

The facility downtime, road closure, or traffic disruption factor has an impact on user satisfaction. Treatments that require less closure time may be favorable over other treatments. Users do not like to experience a closed road for a long period. However, the availability of alternative routes may reduce the importance of this selection factor.

The impact on roughness and friction factors reflect that some treatments affect the pavement roughness and friction negatively while others restore the pavement roughness and friction. For example, crack sealing, and crack filling impact the pavement roughness negatively. Users may experience a rough ride if there are a lot of sealed cracks. Conversely, an HMA overlay or microsurfacing would restore the pavement surface to a smooth ride. Surface friction, on the other hand, is important to safety.

The last factor in the user satisfaction category is tire/road noise. Treatments that produce less noise may be favored over other alternatives.

Procurement and Contracts Factors

The third category in the scoring process is procurement and contracts, which includes two factors:

- Availability of qualified contractors
- Availability of quality material

Certain types of treatments might not be favored. In some cases, experienced or qualified contractors are not located near to the project location and high mobilization costs can be an outcome. Similarly, the availability of quality material is an essential factor to selecting a certain treatment in a specific city or county. In some cases, the availability of qualified contractors or quality construction materials is limited. Materials might need to be hauled for long distances, which affects the project cost and also has negative environmental impacts.

Environmental Sustainability Factor

The last category in the scoring process is environmental sustainability. This category consists of the negative environmental impact factor. Negative environmental impact has to do with the greenhouse gas emissions from various treatments. An asphalt rehabilitation treatment has a higher negative environmental impact compared to a maintenance or a preservation treatment. Treatments with a higher negative environmental impact should receive a lower score than other treatments.

Selection Factor Weighting Process

The ultimate goal of this scoring method is to calculate a score for each feasible treatment based on the selection factors. The importance of each factor will vary from one agency to another. Moreover, the importance of each factor may vary from one person to another in the same agency. As a result, a structured process for determining the weights for each selection factor is needed. A treatment overall score can then be determined by summing the weighted score for each selection factor.

The analytical hierarchy process (AHP) developed by Saaty (1990) has been widely used in many decision-making applications. The AHP is characterized by providing a consistent decision-making process (Akarte et al. 2001) that can help decision makers set priorities and select the best decisions. The AHP is designed to represent complex models in a hierarchical structure. In addition, The AHP is able to handle both quantitative and qualitative attributes (Muralidharan et al. 2002). Therefore, the feasible treatment selection scoring system uses a two-stage AHP.

The first AHP stage is used to determine the weights for each category:

- Cost
- Performance
- User satisfaction
- Procurement and contracts
- Environmental sustainability

The second AHP stage is used to determine the weights for each factor in each category. The two-stage AHP is essentially used for two main reasons. The first is the ease of developing a pairwise comparison between limited numbers of criteria. As the number of criteria increases, inconsistency problems tend to arise. The second reason is the ability to develop pairwise comparisons between criteria with the same nature. For example, it is acceptable to compare factors in the same category together. However, it is inadequate to compare factors from different categories together.

AHP Calculations and Example

A hypothetical example is developed and discussed later in this section to show how the scoring method works. The first stage of the AHP requires agency personnel to develop a matrix of pairwise comparisons between the predefined five categories. Table 45 shows the fundamental scale recommended by Saaty (1990).

Table 45. Fundamental importance scale

Importance Scale	**Definition**
1	Equal importance
3	Moderate importance of one over another
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values

Source: Saaty 1990

Pairwise comparison indicates the importance of one factor over another. Afterward, a transitivity check should be performed. For example, a consistent transitivity means that cost is more important than performance if cost is more important than user satisfaction and user satisfaction is more important than performance. If transitivity is inconsistent, users should reevaluate the pairwise comparison.

The weights of each category can be calculated after checking transitivity. Cardinal consistency should be checked to ensure that decision makers were consistent while conducting the pairwise comparison. For example, if cost is twice as important as performance and performance is three times as important as user satisfaction, then cost should be six times as important as user satisfaction. However, checking cardinal consistency can be a tedious process. Instead, inconsistency can be checked using matrix maximum eigenvalues.

A matrix with perfect consistency should have a maximum eigenvalue equal to the number of factors under consideration. The first step to check consistency is to calculate the consistency index (CI) according to equation 2,

$$CI = \frac{(\lambda_{max} - n)}{n - 1} \tag{2}$$

where λ_{max} is the matrix maximum eigenvalue and n is the number of categories, which is four. A perfect consistency occurs when CI is equal to zero. To determine the decision makers' input consistency, a consistency ratio (CR) is calculated. An acceptable consistency ratio should be less than 10 percent. The consistency ratio is calculated based on equation 3,

$$CR = \frac{CI}{RI} \tag{3}$$

where RI is a random index generated according to the number of factors being included in the scoring.

After determining the weights of each category, the AHP process is repeated four times to calculate the weights for each factor in each category. The global score for each selection factor is calculated based on equation 4,

$$W_g = W_c \times W_l) \tag{4}$$

where W_g is the global weight of a selection factor, W_c is the category weight, and W_l is the local weight of the selection factor.

The following example illustrates the use of the AHP in determining the weights of different factors. Consider the user satisfaction category, which has four factors. First, the decision makers start by developing a pairwise comparison between the different selection factors, as shown in Table 46, by using the fundamental importance scale in Table 45.

Table 46. Sample pairwise comparison for user satisfaction selection factors

	Facility Downtime	Impact on Roughness	Impact of Friction	Tire/Road Noise
Facility Downtime	1	0.50	0.50	0.33
Impact on Roughness	2	1	1	2
Impact of Friction	2	1	1	2
Tire/Road Noise	3	0.5	0.5	1

After developing the pairwise comparison between the different selection factors, values should be normalized as shown in Table 47.

Table 47. Sample priority vector calculation

	Facility Downtime	Impact on Roughness	Impact of Friction	Tire/Road Noise	Column Vector	Weight (Priority Vector)
Facility Downtime	0.13	0.17	0.17	0.06	0.52	0.13
Impact on Roughness	0.25	0.33	0.33	0.38	1.29	0.32
Impact of Friction	0.25	0.33	0.33	0.38	1.29	0.32
Tire/Road Noise	0.38	0.17	0.17	0.19	0.90	0.22

The normalization process is developed by dividing each value by the sum of its column. A column vector is calculated by summing up each row in Table 47.

The priority vector or factor weight is calculated by dividing each column vector by the number of factors. To check the consistency of the user inputs, CI must be calculated.

The first step to calculate the CI is to calculate the λ_{max}, which is the matrix maximum eigenvalue of the pairwise comparison matrix. In this example, λ_{max} is 4.15 and the CI is 0.05. The RI for four selection factors is 0.9. The CR in this case is equal to 0.05, which is less than 0.1. The user inputs are considered to be consistent based on the calculated CR.

Selection Factor Scoring

After determining the weight for each selection factor, a score should be assigned. A scale from 0 to 10 is adopted to assign scores for most selection factors in which 0 represents the lowest performance or highest negative impact and 10 indicates the highest performance or the highest positive impact. However, the scores for expected service life, facility downtime, and EUAC can be calculated directly from their values. As for the expected service life factor, the score can be adjusted according to equation 5,

$$S_i = 10 \times \frac{V_i}{V_{max}} \quad \textbf{(5)}$$

where S_i is the expected service life criterion score for feasible treatment (i), V_i is the expected service life for treatment (i), and V_{max} is the highest expected service life between the set of feasible treatments. Facility downtime and EUAC scores are calculated using equation 6,

$$S_i = 10 \times \frac{V_{min}}{V_i} \quad \textbf{(6)}$$

Finally, after determining all the weights and scores for each factor, the most appropriate treatment can be selected. Each score is multiplied by its weight, and the sum is the overall score for a specific treatment. Equation 7 illustrates the calculation of the treatment overall score,

$$TS_i = \sum_{i,g=1}^{14} S_i \times W_g \quad \textbf{(7)}$$

where TS_i is the treatment score. The selection of the most appropriate treatment should be based on the highest score.

4.5. Treatment Selection Spreadsheet Tool

An Excel-based spreadsheet tool was developed to automate the treatment selection framework, along with a standalone user guide for the tool. The Pavement Treatment Selection Tool (PTST) for Local Agencies consists of input, guidance, and output sheets. The PTST starts with an instruction sheet that briefly explains the spreadsheet tool. Once the user starts the spreadsheet, they are required to enter the basic project information.

Based on the user inputs, the user is navigated to the distress inputs data sheet. A distress identification guide sheet is integrated with the spreadsheet tool. The purpose of the distress identification guide sheet is to reduce subjectivity regarding the distress severity level and extent level decisions.

Once the user enters the existing distress and other pavement attributes, the PTST generates a list of potential actions. One or more treatments can be a potential action for a particular pavement. If only one feasible treatment is recommended, use of the spreadsheet tool terminates there. However, in many cases there will be more than one potential action to apply.

When multiple actions are available, the role of the scoring method becomes essential. The scoring method consists of two stages. The first stage is obligatory while the second stage is optional. The first stage involves a ranking process based on the ROI for each treatment. A synthesis of the treatment cost and data reported by the Iowa DOT and city/county engineers is included in the spreadsheet tool. EUAC is calculated for each scenario, including the do nothing scenario. The ROI is computed for each potential action scenario compared to the do nothing scenario. A list of ranked treatments is generated based on the ROI.

In addition, the PTST allows the user to create future maintenance scenarios. EUAC and ROI are also calculated in these cases. In addition, costs are projected and discounted based on the discount rate entered by the user.

The user has the option to terminate the spreadsheet at this end of the ranking stage or proceed with an advanced ranking method.

The second ranking method consists of non-cost parameters. The second stage ranking process allows agencies to reflect their preferences on their treatment selection decisions. The user is asked whether they prefer to manually assign the weight for each selection parameter or to use the AHP. The PTST allows up to three sets of user input when using the AHP scoring method. The average of the weights is calculated and imported to the final scoring sheet.

The user is required to enter the scores for other selection factors. A weighted score for potential action is computed and a list of ranked actions is generated. In addition, a summary spreadsheet is generated including most of the important inputs and outputs.

5. CONCLUSIONS

Most local agencies such as counties and cities make their pavement treatment decisions based on their anecdotal experience due primarily to lack of a systematic decision-making framework and a decision-aid tool. These local agencies do not need the data intensive asset management and treatment selection processes that are available for pavements managed by state agencies and a data intensive approach may not work for local agencies due to lack of data and resources. However, a structured framework and tool that that can reflect local requirements, practices, and operational conditions would greatly assist local agencies in making consistent and defensible decisions.

This study developed a systematic pavement treatment selection framework and a tool for local agencies. The framework is designed to incorporate local factors such as typical distress patterns and locally available treatment methods in the decision-making process and provide flexibility in assessing pavement conditions and feasible treatments when historical data and numeric condition assessment data are not available.

The treatment selection process involves steps that include pavement condition assessment, selection of technically feasible treatments using decision trees, and selection of the most appropriate treatment considering the lifecycle costs using equivalent uniform annual costs (EUACs) and other non-economic factors.

A comprehensive literature review was conducted to document various treatment methods available in the industry, their technical application boundaries, treatment costs, and expected life expectancies. In addition, pavement maintenance and rehabilitation selection practices were documented as part of the literature review.

A statewide survey questionnaire was conducted to determine common distress types on local pavements, common treatment methods used by local agencies, and any decision-making processes in selecting pavement treatments used by local agencies. The findings from the literature review and the survey questionnaire were appropriately incorporated into developing the pavement treatment selection framework and tool.

This project developed an Excel-based spreadsheet tool that automates the process of the treatment selection framework. The tool requires local agencies to input basic project information and distress data so the tool can generate a list of technically feasible treatments. After that, EUAC and ROI are calculated automatically based on the discount rate entered by the user. This Excel tool offers flexibility by allowing users to override default values of treatment costs and performance data using their local data and local agencies are encouraged to use their own performance data to accurately assess the cost effectiveness for each alternative.

It is expected that the framework and tool will help local agencies improve their pavement asset management practices significantly and make better economic and defensible decisions on pavement treatment selection.

REFERENCES

Ahmed, A. 2012. *Pavement Damage Cost Estimation Using Highway Agency Maintenance, Rehabilitation, and Reconstruction Strategies*. Purdue University, West Lafayette, Indiana.

Akarte, M. M., Surendra, N. V., Ravi, B., and Rangaraj, N. 2001. Web based casting supplier evaluation using analytical hierarchy process. *Journal of the Operational Research Society*. 52, pp. 511-522.

American Society of Civil Engineers (ASCE). 2013. *Report Card for America's Infrastructure*. www.infrastructurereportcard.org/a/documents/Roads.pdf

American Society of Civil Engineers (ASCE). 2015. *Infrastructure Report Card-2009 Grades*. www.infrastructurereportcard.org/state-page/iowa.

Bektas, Fatih, Omar Smadi, and Mazin Al-Zoubi. 2014. *Pavement Management Performance Modeling: Evaluating the Existing PCI Equations*. Institute for Transportation, Iowa State University. Ames, IA.

Bolander, P. W. 2005. Seal Coat Options: Taking Out the Mystery. *Transportation Research Circular No. E-C078: Roadway Pavement Preservation 2005*. Papers from the First National Conference on Pavement Preservation. Kansas City, MO. October 31-November 1, 2005. pp. 24-41.

Cambridge Systematics, Inc. 2008. *NCHRP Report 8-36: Best Practice Methodology for Calculating Return on Investment for Transportation Programs and Projects*. Transportation Research Board, Washington, DC.

California Department of Transportation (Caltrans). 2009. *Maintenance Technical Advisory Guide (MTAG) Volume I – Flexible Pavement Preservation*. Second Edition www.dot.ca.gov/hq/maint/MTA_GuideVolume1Flexible.html.

California Department of Transportation (Caltrans). 2006. *Open Graded Friction Course Usage Guide*. Division of Engineering Services, Sacramento, CA.

California Department of Transportation (Caltrans). 2003. *Framework for Treatment Selection*. Caltrans Division of Maintenance, Sacramento, CA.

Ceylan, H., Gopalakrishnan, K., and Kim, S. 2008. Rehabilitation of Concrete Pavements Utilizing Rubblization and Crack and Seat Methods (Phase II): Performance Evaluation of Rubblized Pavements in Iowa. National Concrete Pavement Technology Center. Ames, IA.

Cook, M. C., Seeds, S. B., Zhou, H., and Hicks, R. Gary. 2004. Guide for Investigating and Remediating Distress in Flexible Pavements: California Department of Transportation's New Procedure. *Transportation Research Record: Journal of the Transportation Research Board*, 1896(1), 147-161.

Dawson, T. A. 2012. Evaluation of pavement management data and analysis of treatment effectiveness using multi-level treatment transition matrices. PhD dissertation. Michigan State University.

Dawson, T. A., Dean, C., Haider, S. W., and Chatti, K. 2011. Selection of Optimum Pavement Treatment Type and Timing at the Project Level. TRB 2011 Annual Meeting. Washington, DC.

Federal Highway Administration (FHWA). 2005. Pavement Preservation Definitions [Memorandum]. www.fhwa.dot.gov/pavement/preservation/091205.cfm. (Last accessed October 8, 2015.)

Flora, W. F. 2009. Development of a structural index for pavement management: An exploratory analysis. Master's thesis. Purdue University.

Hicks, R. Gary, Seeds, S. B., and Peshkin, D. G. 2000. *Selecting a Preventive Maintenance Treatment for Flexible Pavements*. Foundation for Pavement Preservation, Washington, DC.

Huang, Y. H. 1993. *Pavement Analysis and Design*. Prentice-Hall, Englewood Cliffs, NJ.

Illinois Department of Transportation (IDOT). 2014. *Illinois Highway Information System Roadway Information and Procedure Manual Appendix C*. Illinois Department of Transportation. Springfield, IL.

Illinois Department of Transportation (IDOT). 2010. *Pavement Preservation Chapter 52*. Illinois Department of Transportation: Bureau of Design & Environment Manual. Springfield, IL.

Illinois Department of Transportation (IDOT). 2005a. *Pavement Technology Advisory: Bonded Concrete Overlay*. Illinois Department of Transportation: Bureau of Materials and Physical Research. Springfield, IL.

Illinois Department of Transportation (IDOT). 2005b. *Pavement Technology Advisory: Unbonded Concrete Overlay*. Illinois Department of Transportation: Bureau of Materials and Physical Research. Springfield, IL.

International Grooving and Grinding Association (IGGA). 2010. *Dowel Bar Retrofit: Rebuilt to Last*. International Grooving and Grinding Association. Coaxsackie, NY.

Iowa Department of Transportation (DOT). 2012. *Road Use Tax Fund Efficiency Report*. Iowa Department of Transportation. Ames, IA. www.iowadot.gov/pdf_files/RUTFefficiencies.pdf. (Accessed October 8, 2015.)

Jahren, C., Smith, D., and Plymesser, C. 2007. *Thin Maintenance Surfaces for Municipalities*. Center for Transportation Research and Education, Iowa State University. Ames, IA.

Johnson, A. M. 2000. *Best Practices Handbook on Asphalt Pavement Maintenance*. Minnesota Department of Transportation, St. Paul, MN.

Kay, R. K. 1992. *Pavement Surface Condition Rating Manual*. Washington State Transportation Center. University of Washington. Seattle, WA.

Labi, S., Lamptey, G., and Kong, S. H. 2007. Effectiveness of Microsurfacing Treatments. *Journal of Transportation Engineering, 133*(5), 298-307.

Lee, J., and Shields, T. 2010. *Treatment Guidelines for Pavement Preservation*. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, IN.

Li, J., Luhr, D. R., Uhlmeyer, J. S., and Mahoney, J. P. 2012. Preservation Strategies for Concrete Pavement Network of Washington State Department of Transportation. *Transportation Research Record: Journal of the Transportation Research Board*. 2306(1), 11-20.

Li, Y., Cheetham, A., Zaghloul, S., Helali, K., and Bekheet, W. 2006. Enhancement of Arizona Pavement Management System for Construction and Maintenance Activities. *Transportation Research Record: Journal of the Transportation Research Board, No. 1974*. Transportation Research Board of the National Academies. Washington, DC. pp. 26-36.

Maher, M., Marshall C., Harrison F., and Baumgaertner K. 2005. *Context Sensitive Roadway Surfacing Selection Guide*. Federal Highway Administration Central Federal Lands Highway Division, Colorado.

Michigan Department of Transportation (MDOT). 2003. *Capital Preventive Maintenance Manual*. Michigan Department of Transportation, Construction and Technology Division.

Miller, John S., and William Y. Billenger 2003. *Distress Identification Manual for the Long-Term Pavement Performance Program*. Federal Highway Administration. Washington, DC.

Minnesota Department of Transportation (MnDOT). 2012a. Network Level Bit & BOC Decision Tree (07/01/12). www.dot.state.mn.us/materials/pvmtmgmtdocs/Bituminous_Decision_Tree_07-01-12.pdf. (Last accessed August 13, 2015.)

Minnesota Department of Transportation (MnDOT). 2012b. Network Level Concrete Decision Tree (06/21/12). www.dot.state.mn.us/materials/pvmtmgmtdocs/Concrete_Decision_Tree_07-01-12.pdf. (Last accessed August 13, 2015.)

Minnesota Department of Transportation (MnDOT). 2011. *RIDE-Pavement Management Vans*. Minnesota Department of Transportation.

Minnesota Department of Transportation (MnDOT). 2006. *An Overview of Mn/DOT's Pavement Condition Rating Procedures and Indices*. Minnesota Department of Transportation Office of Materials and Road Research Pavement Management Unit. Maplewood, MN.

Minnesota Department of Transportation (MnDOT). 2003. *Mn/DOT Distress Identification Manual*. Minnesota Department of Transportation Office of Materials and Road Research Pavement Management Unit. Maplewood, MN.

Missouri Department of Transportation (MoDOT). 2002. *Missouri Guide for Pavement Rehabilitation*. Jefferson City, MO.

Morian, D. 2011. *Cost Benefit Analysis of Including Microsurfacing in Pavement Treatment Strategies and Cycle Maintenance*. Commonwealth of Pennsylvania Department of Transportation, Harrisburg, PA.

Muralidharan, C., Anantharaman, N., and Deshmukh, S. G. 2002.A Multi-Criteria Group Decision-making Model for Supplier Rating. *Journal of Supply Chain Management*. 38(3), pp. 22-33.

Nebraska Department of Roads (NDOR). 2002. *Pavement Maintenance Manual*. Nebraska Department of Roads. Lincoln, NE.

Ohio Department of Transportation (ODOT). 2001. *Pavement Preventive Maintenance Program Guidelines*. Ohio Department of Transportation. Columbus, Ohio.

Peshkin, D. G., Hoerner, T. E., and Zimmerman, K. A. 2004. *NCHRP Report 523: Optimal Timing of Pavement Preventive Maintenance Treatment Applications*. National Cooperative Highway Research Program. Transportation Research Board of the National Academies. Washington, DC.

Pittenger, D., Gransberg, D. D., Zaman, M., and Riemer, C. 2011. Life-Cycle Cost-Based Pavement Preservation Treatment Design. *Transportation Research Record No. 2235: Journal of the Transportation Research Board*. pp. 28-35.

Raza, H. 1992. *An Overview of Surface Rehabilitation Techniques for Asphalt Pavements*. Federal Highway Administration. Washington, DC.

Russell, M. A., L. M. Pierce, J. S. Uhlmeyer, and K. W. Anderson. 2008. *NovaChip®*. Experimental Feature Report. Washington State Department of Transportation, Olympia, WA.

Saaty, T. L. 1990. How to make a decision: the analytic hierarchy process. *European Journal of Operational Research*. 48(1), 9-26.

Sayers, M. W., Gillespie, T. D., and Queiroz, C. A. V. 1986. The international road roughness experiment: Establishing correlation and a calibration standard for measurements. In *World Bank Technical Report*. The World Bank. Washington, DC.

Shahin, M. Y. 1994. *Pavement management for airports, roads, and parking lots*. Chapman & Hall, New York.

Shahin, M. Y. and Walther, J. A. 1990. *Pavement Maintenance Management for Roads and Streets Using the PAVER System*. U.S. Army Corps of Engineers, Civil Engineering Research Laboratory, Champaign, IL.

Smith, Kurt. 2005. *Concrete Pavement Rehabilitation and Preservation Treatments*. Tech Brief. U.S. Department of Transportation Federal Highway Administration Concrete Pavement Technology Program (CPTP).

Smith, K., Hoerner, T. E., and Peshkin, D. G. 2008. *Concrete Pavement Preservation Workshop*. National Concrete Pavement Technology Center. Ames, IA.

South Dakota Department of Transportation (SDDOT) 2010. *Pavement Preservation Guidelines*. South Dakota Department of Transportation. Pierre, SD.

Utah Department of Transportation (UDOT) 2009. *Pavement Preservation Manual-Part 3: Preservation Treatments*. Utah Department of Transportation Office of Asset Management.

Villacres, J. 2005. *Pavement Life-Cycle Cost Studies Using Actual Data Cost—A Synthesis*. Asphalt Pavement Alliance, Lanham, MD.