District Level Decision Making Tool for Preventive Maintenance Treatment Selection in Virginia

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ABSTRACT

Preventive maintenance has the potential to improve network condition by retarding future pavement deterioration. The Virginia Department of Transportation uses its pavement management system to determine maintenance targets for each district. The districts then use these recommendations to select pavements that will receive maintenance and the types of treatments that will be applied. Each district has a different approach to preventive maintenance. There was a need for more consistent preventive maintenance practices across the state.

This thesis outlines guidelines for the implementation of a preventive maintenance policy. Preventive maintenance treatments currently being used within Virginia include chip seal, slurry seal, microsurfacing, and thin hot mix asphalt overlays. Historical pavement condition data was obtained from the VDOT PMS for these treatments and treatment performance models were developed. A district level treatment selection tool was developed to assist the district level decision making process. A prioritized list of pavement sections was generated, maximizing the cost-effectiveness of the selected treatments subject to budgetary constraints set by the central office.

The treatment selection tool was then run for each pavement classification in each district. The results of this analysis were presented. Although the recommended budget for each district was very close to the targets set by the central office, the recommended lane miles for each district were about half the targets set by the central office. It is believed that the unit costs used in this analysis were higher than those used in the VDOT PMS analysis. This selection tool has the potential to be a very powerful decision support tool if the unit costs are representative of what the expected treatment costs are for each district.

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LIST OF ABBREVIATIONS

A.A.S.H.T.O.	American Association of State Highway and Transportation Officials
A.C.	Asphalt Concrete
A.D.T.	Average Daily Traffic
A.H.P.	Analytical Hierarchy Process
B.C.R.	Benefit-Cost Ratio
B.I.T.	Bituminous Pavement
B.O.C.	Bituminous Over Continuously Reinforced Concrete Pavement
B.O.J.	Bituminous Over Jointed Reinforced Concrete Pavement
C.C.I.	Critical Condition Index
C.M.	Corrective Maintenance
C.R.C.	Continuously Reinforced Concrete Pavement
D.N.	Do Nothing
D.I.	Distress Index
D.O.T.	Department of Transportation
E.I.	Effectiveness Index
G.H.G.	Green House Gas
G.I.S.	Geographic Information System
H.M.A.	Hot Mix Asphalt
H.M.A.O.L.	Hot Mix Asphalt Overlay
I.B.C.	Incremental Benefit-Cost
I.R.I.	International Roughness Index
J.R.C.	Jointed Reinforced Concrete Pavement
L.C.C.A.	Life Cycle Cost Analysis
L.D.R.	Load-related Distress Rating
M.C.E.	Marginal Cost Effectiveness
M.D.O.T.	Michigan Department of Transportation
M.U.	Maintenance Unit
N.C.H.R.P.	National Co-Operative Highway Research Program
N.D.R.	Non-load-related Distress Rating
N.O.V.A.	Northern Virginia

P.C.I.	Pavement Condition Index
P.M.	Preventive Maintenance
P.M.I.S.	Pavement Management and Information System
P.M.S.	Pavement Management System
R.C.	Rehabilitation and/or Reconstruction
R.M.	Restorative Maintenance
R.Q.I.	Ride Quality Index
S.H.A.	State Highway Administration
S.H.R.P.	Strategic Highway Research Program
T.H.M.A.C.O.	Thin Hot Mix Asphalt Concrete Overlay
Tx.D.O.T.	Texas Department of Transportation
V.D.O.T.	Virginia Department of Transportation

CHAPTER I - INTRODUCTION

BACKGROUND

Preventive Maintenance

Maintaining road conditions to acceptable standards can be quite costly with traditional pavement maintenance approaches [1]. Pavement preservation can be defined as "a program employing a network level, long-term strategy that enhances functional pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety, and meet motorist expectations" [2]. Pavement preservation is a general category of road maintenance which consists of three components: minor rehabilitation, routine maintenance, and preventive maintenance [2].

Although the terms "pavement preservation" and "preventive maintenance" are often used interchangeably, preventive maintenance is in fact a subset of pavement preservation. The concept of preventive maintenance involves maintaining the functional condition of roadway systems without improving their structural capacity by strategically applying cost-effective treatments [3]. Preventive maintenance seals the pavement surface and prevents water from infiltrating into the pavement structure. These treatments, therefore, prolong pavement life and maintain the pavement in an acceptable state for a longer period of time. Preventive maintenance is being promoted so that pavements can still benefit from reduced levels of funding—state departments of transportation simply cannot afford to do the same levels of maintenance and rehabilitation that have been carried out in the past [4]. Highway agencies with limited funding can use preventive maintenance so that "pavements can be maintained in a cost-effective manner leading to a better pavement quality at lower total costs" [1]. This concept is illustrated in Figure 1.

Preventive maintenance treatments are often applied to pavements in relatively good condition, and retard future deterioration of the pavement structure. Highway agencies are now moving towards a preventive maintenance approach instead of traditional worst-first policies so that pavements are no longer allowed to deteriorate to a very poor condition before major rehabilitation is performed [5].

With growing concerns about environmental impact of our built infrastructure, sustainability is becoming a common theme amongst road agencies. The principle of sustainability requires consideration of economic, social, and environmental progress while meeting human needs for the present and future [6]. The criteria outlined in [7] identify the characteristics of a sustainable pavement:

- Optimized use of available resources
- Reduced energy consumption, Green House Gas (GHG) emission, and pollution
- Improved health and safety
- Increased user comfort

Preventive maintenance treatments satisfy these criteria listed for sustainable pavements. Preventive maintenance treatments, when compared to traditional treatments (such as milling with hot mix asphalt overlays) are generally thinner, have faster application rates, are less disruptive, produce less greenhouse gas emissions, and consume less energy [8]. These benefits, combined with the theory that pavements which are part of a preventive maintenance program are able to maintain a higher level of performance over the pavement's life, support the idea of preventive maintenance as a tool for increasing the sustainability of our transportation infrastructure.

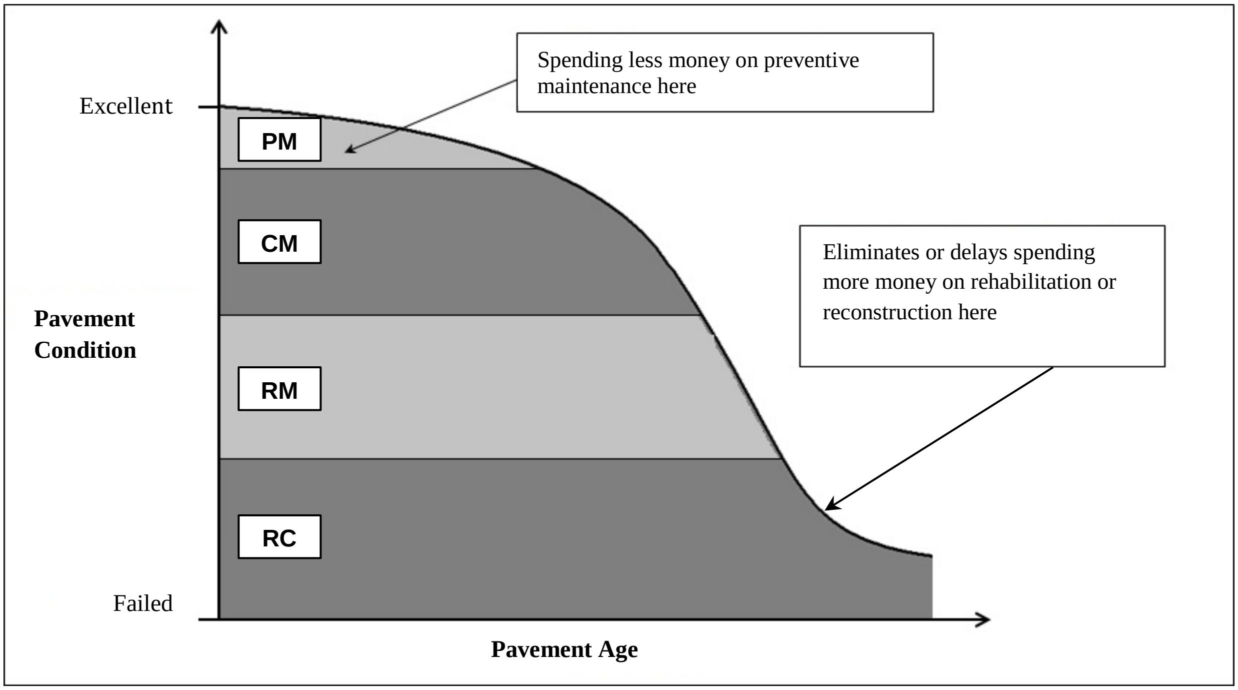


Figure 1. Preventive Maintenance Benefits [9]

However, some agencies still avoid preventive maintenance treatment application on high-volume roads because of major concerns regarding the liability that is associated with the potential failure of the treatment. Furthermore, treatments applied to high-volume roads may not be as effective as treatments applied to low-volume roads because there may be a faster rate of deterioration due to traffic. It must be noted, however, that preservation of both high-volume and low-volume roads is necessary because of the need to maximize the benefit of limited maintenance budgets, and the potential improvement in ride quality and safety [10].

Possible preventive maintenance treatments include the following, which are described in detail in Chapter II:

- Crack Seal
- Slurry Seal
- Chip Seal
- Microsurfacing
- Cape seal
- Ultra-Thin friction course
- Thin and Ultra-Thin Hot Mix Asphalt Overlay

Pavement Management Systems and Preventive Maintenance

The American Association of State Highway and Transportation Officials (AASHTO) published a guide for pavement management in 2001 outlining the technologies available and relevant processes pertaining to pavement management. This guide defines pavement management as "a management approach used by personnel in an agency to make decisions" and defines a pavement management system (PMS) as "a set of tools used to assist decision-makers at all levels in making better and more informed decisions" [11].

The network-level decision making process has become more efficient with the advent of pavement management systems. A PMS provides a centralized database that can be used to store pavement data, analyze past pavement performance, predict future pavement performance, recommend maintenance strategies, and forecast the effect of different types of maintenance on network level performance. It allows highway agencies the means to justify maintenance strategies to external entities such as state and federal officials or the general public. It also has the ability to strategically improve network condition over time through managed long-term goals.

A PMS is an important tool in the development of preventive maintenance policies. A PMS can demonstrate the key benefit to preventive maintenance: preventing potentially costly rehabilitation by maintaining good pavement condition.

One possible benefit of integrating PMSs with preventive maintenance is the possibility for prioritization and optimization within the pavement management process. Preventive maintenance operations can be run in tandem with major rehabilitation so that poor pavements are improved while good pavements maintain their good condition. It should be noted, however, that performance of preventive maintenance treatments should be monitored so that prediction models can be refined and their expected benefit specific to the desired road network can be estimated [12].

Virginia Department of Transportation Current Maintenance Practices

The Virginia Department of Transportation (VDOT) uses three condition indices to rate pavement distresses in Virginia. The first index is the Load-Related Distress Rating (LDR) which measures pavement distresses which are load-related. The second index is the Non-Load-Related Distress Rating (NDR) which measures pavement distresses which are not load-related, such as those caused by environmental or climatic conditions. These two condition indices are rated on a scale of 0 to 100, where 100 is a pavement having no distresses present. The third index is the Critical Condition Index (CCI) which is the lower of the LDR and NDR [13].

VDOT defines a deficient pavement as one which has a CCI value below 60. The statewide target for Interstate and Primary route condition is to have $\leq$ 18% of these pavements rated deficient [14]. The deficiency for each district is illustrated in Figure 2.

Each district has different levels of pavement deficiency. Many factors can have an effect on pavement condition, such as maintenance budget, maintenance policies, traffic, climate, etc. There is currently no statewide standard for an accepted preventive maintenance policy. Through speaking to district engineers at three district visits, it was found that Salem district applies preventive maintenance to pavements with a CCI greater than 85, Richmond applies preventive maintenance to pavements with a CCI between 75 and 85, and Northern Virginia (NOVA) applies preventive maintenance to pavements with a CCI between 80 and 89. This disparity in preventive maintenance policy could be a contributing factor to differences in district deficiencies.

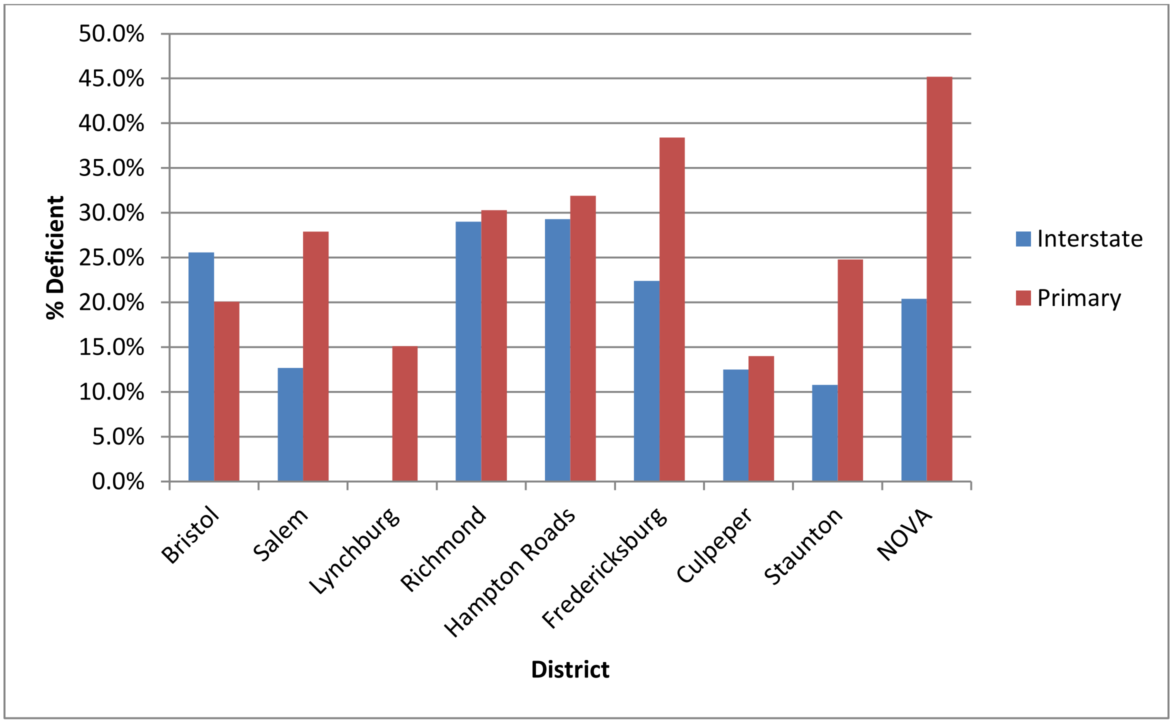


Figure 2. Percent Deficiency by District for Interstate and Primary Routes [14]

The Virginia Department of Transportation Pavement Management System

VDOT currently uses a PMS developed by AgileAssets [15]. This system performs network-level multi-constraint optimization, which develops a work plan using single objectives and multiple constraints. The objective can be either to minimize cost while achieving specified performance targets, or to maximize performance while satisfying budgetary concerns. The output of this optimization analysis is the recommended treatment category for each section: Do Nothing (DN), Preventive Maintenance (PM), Corrective Maintenance (CM), Restorative Maintenance (RM), or Rehabilitation and/or Reconstruction (RC).

The PMS performs two analyses for maintenance needs: unconstrained needs analysis and constrained needs analysis. The unconstrained needs analysis, or total needs, provides the cost of all work performed based on recommended treatment selections for each pavement. The constrained needs analysis can be used to determine any of the following:

- The cost required to maintain the network in its current condition
- The cost required to achieve and maintain a desired condition for the network
- The effect of a given budget on network condition

The VDOT Central office generates reports from the PMS that provides maintenance targets for each district. Recommended budget and numbers of lane miles are provided for each maintenance category (DN, PM, CM, RM, RC). The district engineer uses these recommendations along with the unconstrained analysis to decide which pavements are selected for maintenance and which treatments are applied.

PROBLEM STATEMENT

The VDOT central office provides recommendations to each district regarding treatment categories, budget, and total lane miles to be maintained within each category. District engineers select which pavements receive maintenance along with the specific treatment applied to these pavements. Over time, each district has developed its own preventive maintenance policy, and there is a statewide disparity regarding preventive maintenance treatment selection. Districts have different criteria that can qualify a pavement for consideration for preventive maintenance, and treatment selection is based upon engineering experience. Guidelines for the use of preventive maintenance are needed.

OBJECTIVES

The objectives of this thesis are to use data available through the VDOT PMS to

- Assess the current preventive maintenance practices within the state;
- Develop a district level decision making tool that can be used by the maintenance districts in Virginia to determine the optimal treatment selection for each pavement maintenance section and provide a prioritized list of pavements to receive these treatments; and
- Develop statewide guidelines for implementation of a preventive maintenance policy so that each district can make their decisions using consensus-based guidelines.

RESEARCH SCOPE

To accomplish the objectives of this study, a review of available literature and current state practices were conducted. Pavement condition data was obtained from the VDOT PMS. This data was analyzed to develop treatment performance models for each of the four preventive maintenance treatments considered in this study: Microsurfacing, Slurry Seal, Chip Seal, Thin Hot Mix Asphalt Concrete Overlay (THMACO). A user friendly district level selection tool was developed using a visual basic enhanced Microsoft Excel workbook. Treatment feasibility and cost were determined using resources obtained from review of previous studies.

Chapter II provides a literature review of available preventive maintenance treatments and methods used in the development of selection tools: performance prediction and modeling, decision trees and matrices, scoring systems, and operations research. It also presents case studies showing previous approaches. Chapter III outlines the current practices in Virginia. Chapter IV presents recommendations for implementation of a preventive maintenance policy. Chapter V outlines the development of the treatment performance models and the development of the treatment selection tool. Chapter VI summarizes the findings and provides conclusions and presents recommendations for future work.

CHAPTER II - LITERATURE REVIEW

BACKGROUND

Preventive Maintenance, which is the focus of this thesis, can be defined as "a planned strategy of cost-effective treatments applied to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system (without increasing its structural capacity)" [3].

BENEFITS OF PREVENTIVE MAINTENANCE

Preventive maintenance is generally applied to address environmentally related distresses. Renewal of the pavement surface provides waterproofing as well as replacement of volatile components lost due environmental conditions. Since preventive maintenance addresses environmentally related distresses, its placement should be based on time rather than traffic on a roadway. Furthermore, if pavement distresses are related to structural deficiencies within the pavement, preventive maintenance should not be applied [16].

When compared to conventional pavement maintenance methods, preventive maintenance treatments are typically thinner, easier to construct with less traffic disruption, and are more cost-effective [17].

Although preventive maintenance applied to structurally deficient pavements can delay necessary rehabilitation for a short period of time, these treatments are not cost-effective in the long term. When there is a backlog of pavements that need major rehabilitation, agencies must work to find a balance between improving these pavements in poor condition while preventing pavements in good condition from deteriorating such that preventive maintenance treatments are no longer effective [11].

Preventive maintenance has numerous potential benefits, which include improved user satisfaction, significant savings in cost, extension of life, and increased safety [17]. The Michigan Department of Transportation has been able to show that implementation of preventive maintenance strategies optimizes network condition, resulting in greater stability in funding needs [16].

DESCRIPTION OF COMMON PREVENTIVE MAINTENANCE ACTIVITIES

Crack Seals

Crack seals are defined as the placement of an adhesive material into or over working cracks for the main purpose of preventing the infiltration of moisture into the pavement [18]. An illustration of a crack seal application is shown in Figure 3.

Crack seals can be applied to structural cracks. Although it provides no structural benefit, it keeps moisture out of the pavement and therefore slows the progression of load related distresses. If crack seals are improperly installed, the sealant material may fail. Overband applications of the crack seal are susceptible to snow plow damage [18].

Crack seals should be placed when the pavement's condition index falls within the range of 80 to 95 and the pavement is between 2 to 5 years old. It is highly recommended to be used on urban and rural roads, regardless of traffic level. It is highly recommended for overnight or single shift work zone durations [18].

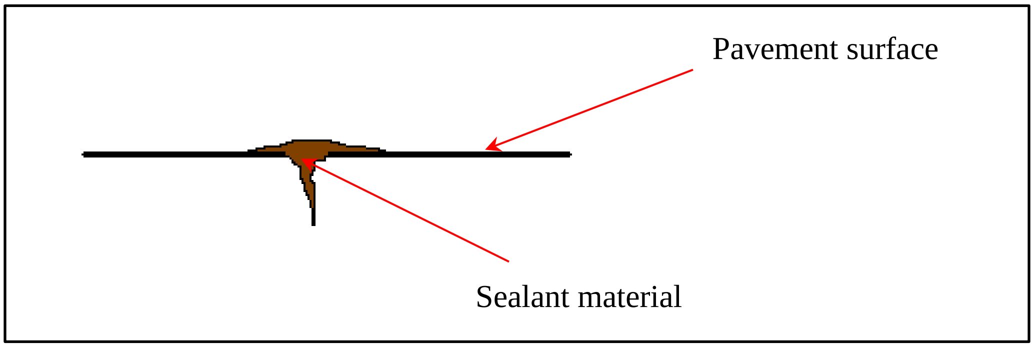


Figure 3. Crack Seal

Chip Seals

Chip seals are commonly referred to as surface treatments, and are used to improve friction and seal pavements which have non-load-related cracking [17]. A chip seal may be defined as a sprayed application of asphalt followed by the application of aggregate chips which are immediately rolled to achieve 50% to 70% embedment. A chip seal may be applied in a single layer or a double layer where a layer of large aggregate is placed first, followed by a layer of smaller aggregate [18]. An illustration of a chip seal is shown in Figure 4.

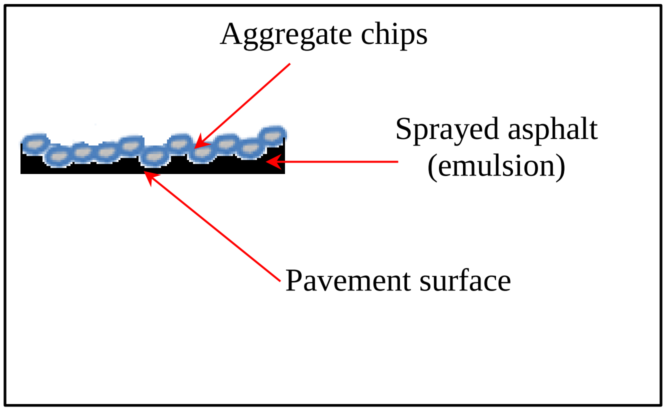


Figure 4. Chip Seal

Pavement condition is an important consideration when placing the chip seal. Single or double course chip seals should typically be placed when the pavement's condition index falls within the range of 70 to 85 and the pavement is between 5 to 8 years old. It is generally recommended to be used on high traffic ADT rural roads (>5,000vpd) or urban roads (>10,000vpd) [18].

Curing typically takes 2 hours, after which normal traffic speeds may resume [18].

Chip seals used on high volume roadways can result in excess dust, roughness, and noise, and potentially damage to cars due to loose chips. The expected life of this treatment is considerably shorter when applied to high traffic volume roads when compared to low traffic volume roads. It is possible, however, to limit the occurrence of loose chips by using design or construction modifications. Using a polymer-modified binder or application of a sprayed layer of asphalt emulsion on the surface of the seal, or even sweeping the chip seal after application can all potentially improve the quality of the chip seal [17].

Slurry Seals

A slurry seal may be defined as a mixture of well-graded fine aggregate and asphalt emulsion [17]. This mixture is spread over the surface of the pavement with a spreader box fitted to the back of the truck [18]. An illustration of a slurry seal application is shown in Figure 5.

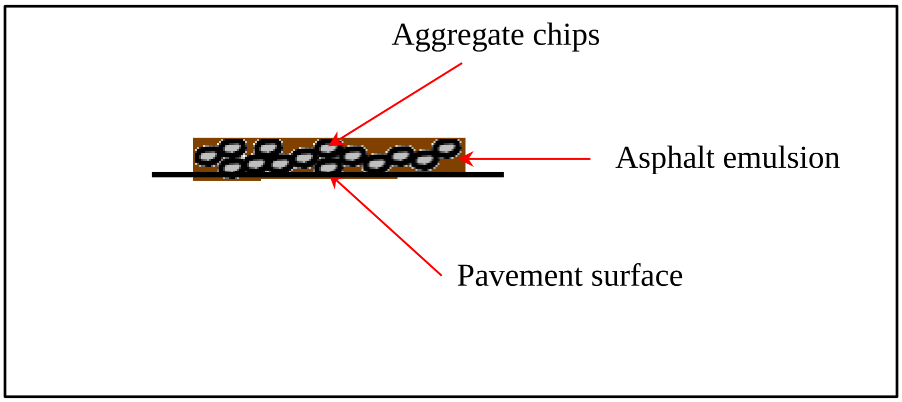


Figure 5. Slurry Seal

Pavement condition is an important consideration when placing the slurry seal. It may be used to address certain functional distresses, however, slurry seals should not be placed on pavements with structural deficiencies as they do not add structural capacity [18]. If there are any areas of localized distress, these should be repaired prior to application of the slurry seal [17].

Climate is also an important consideration for a slurry seal since it requires several hours to cure in warm temperatures with direct sunlight. If these conditions cannot be guaranteed and if traffic cannot be kept off the pavement long enough, another treatment should be used [18].

Slurry seals should be placed when the pavement's condition index falls within the range of 70 to 85 and the pavement is between 5 to 8 years old. It is provisionally recommended to be used on high traffic Average Daily Traffic (ADT) rural roads (>5,000vpd) or urban roads (>10,000vpd) [18].

Microsurfacing

Microsurfacing is a mixture of crushed, well-graded aggregate, mineral filler, and latex-modified asphalt that is placed on the pavement surface with a squeegee or spreader box [18]. Microsurfacing is very similar to a slurry seal, however the binder is polymer-modified and there are higher quality aggregates [17]. Microsurfacing can be placed in a single or double application. The double application involves a rut-filling application followed by a full-surface application [18].

Single or double course microsurfacing should be placed when the pavement's condition index falls within the range of 70 to 85 and the pavement is between 5 to 8 years old. It is generally recommended to be used on high traffic ADT rural roads (>5,000vpd) or urban roads (>10,000vpd) [18].

Microsurfacing is widely accepted for use on high-traffic-volume roadways [17]. There is minimal disruption to traffic since curing typically takes 1 hour, after which traffic may resume [18].

Cape Seal

A cape seal is a combination of a chip seal and a slurry seal. The slurry seal is placed above the chip seal approximately 4 to 10 days after the initial chip seal application. The cape seal is used for the same purpose as a chip seal, however, the slurry seal extends the life of the chip seal since it forms a protective layer over it that improves the binding of the aggregate chips [18].

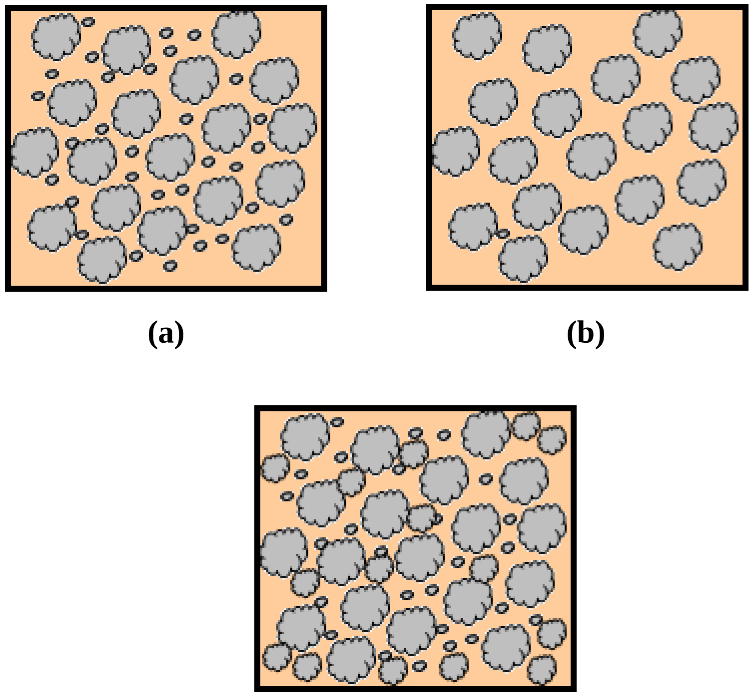
Ultra-Thin Friction Course

This treatment is also known as an ultra-thin bonded wearing course. It consists of a gap graded, polymer modified HMA layer (approximately 0.4" to 0.8" thick) placed on a tack coat [18]. A gap graded aggregate consists of coarse grades and fine grades of aggregate without having any medium grades, hence the "gap" in the grading [17]. An illustration of a gap-graded aggregate modified from [17] is shown in Figure 6.

An ultra-thin friction course should be placed when the pavement's condition index falls within the range of 65 to 85 and the pavement is between 5 to 10 years old. It is generally recommended to be used on high traffic ADT rural roads (>5,000vpd) or urban roads (>10,000vpd). It is highly recommended for overnight or single shift work zone durations [18].

Ultra Thin and Thin Hot Mix Asphalt Overlays

These overlays are composed of asphalt binder and aggregate combined in a paving machine and laid on an existing pavement (milled or unmilled). These overlays can be gap-graded, dense-graded, or open-graded [17]. Open-graded aggregates predominantly consist of aggregates which are the same size, as shown in Figure 6. Dense-graded aggregates are well graded and the aggregate sizes are uniformly distributed. Dens-graded aggregates are shown in Figure 6. Milling is recommended when surface distresses are evident [18].



(a) (b) (c)

Figure 6. Illustration of (a) Gap-graded aggregate, (b) Open-graded aggregate, and (c) Dense-graded aggregate, after [17]

An ultra-thin hot mix asphalt overlay (HMAOL) should be placed when the pavement's condition index falls within the range of 65 to 85 and the pavement is between 5 to 10 years old. It is generally recommended to be used on high traffic ADT urban roads (>10,000vpd). It is highly recommended for overnight or single shift work zone durations [18].

A thin HMAOL should be placed when the pavement's condition index falls within the range of 60 to 80 and the pavement is between 6 to 12 years old. It is highly recommended to be used on high traffic ADT rural roads (>5,000vpd) or urban roads (>10,000vpd). It is highly recommended for overnight or single shift work zone durations [18].

FEASIBILITY OF PREVENTIVE MAINTENANCE TREATMENTS

According to Johnson [16], appropriate preventive maintenance treatments for each type of pavement distress are shown in Table 1 and Table 2. Table 1 shows preventive maintenance treatment feasibility for addressing each type of surface cracking, while Table 2 shows the preventive maintenance treatment feasibility for addressing area-wide pavement distresses. Another decision matrix developed by Hicks et al. [19] is shown in Table 3. The predominant preventive maintenance treatments for each type of pavement distress from a Strategic Highway Research Program (SHRP) 2 report [18] are shown in Table 4.

Table 1. Feasible Treatments for Cracks [16]

Crack Type	Severity	Treatment			
		Crack Filling	Patching	Chip Seal	Thin Overlay
Alligator	Low			✓	
	Medium		✓		
	High		✓		
Transverse	Low			✓	
	Medium	✓		✓	
	High	✓	✓	✓	
Longitudinal	Low	✓			
	Medium	✓			
	High	✓	✓		
Block	Low			✓	
	Medium			✓	✓
	High	✓	✓		✓
Reflective	Low				
	Medium	✓			
	High	✓	✓		✓

Table 2. Feasible Treatments for Surface Distresses [16]

Distress Type	Severity	Treatment			
		Double Chip Seal	Slurry Seal	Microsurfacing	Thin Overlay
Rutting	Low		✓	✓	
	Medium		✓	✓	✓
	High			✓	✓
Bleeding	Low	✓	✓	✓	
	Medium	✓	✓	✓	
	High	✓	✓	✓	✓
Polishing	Low	✓	✓	✓	
	Medium	✓	✓	✓	✓
	High	✓	✓	✓	✓
Raveling	Low				
	Medium				
	High	✓	✓	✓	✓

Table 3. Feasible treatments for Distresses [19]

Distress	Crack Seal	Microsurfacing	Slurry Seal	Chip Seal	Thin Overlay
Roughness		✓			✓
Rutting		✓	✓		✓
Fatigue Cracking					
Longitudinal/ Transverse Cracking	✓	✓	✓	✓	✓
Bleeding		✓			
Raveling		✓	✓	✓	

Table 4. Treatment Feasibility Matrix for Cracking Distresses, after [18]

Distress	Fatigue/ Long Wheel Path/ Slippage			Block			Transverse Thermal			Joint Reflective			Long/ Edge			Raveling/ Weathering			Bleeding/ Flushing	Polishing	Segregation			Water Bleeding/ Pumping	Wear/ Stable Rutting			Patching			Ride Quality	Friction	Noise
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H			L	M	H		L	M	H	L	M	H			
Crack Fill	✗	✗	✗	✓		✗		✗	✗		✗	✗	✓	✓																			
Crack Seal	✗	✗	✗	✓		✗	✓	✓		✓	✓			✗	✗																		
Slurry Seal	✓		✗	✓	✓		✓		✗	✓		✗	✓		✗	✓	✓	✓	✗	✓	✓		✗	✓		✗	✗	✓		✗	✗	✓	✓
Microsurfacing: Single	✓		✗	✓	✓		✓		✗	✓		✗	✓		✗	✓	✓	✓	✗	✓	✓	✓		✓	✓		✗	✓		✗		✓	✓
Microsurfacing: Double	✓		✗	✓	✓		✓	✓		✓	✓		✓	✓		✓	✓	✓	✗	✓	✓	✓			✓	✓		✓	✓		✓	✓	✓
Chip Seal: Single Conventional	✓		✗	✓	✓		✓	✓		✓	✓		✓	✓		✓	✓	✓		✓	✓	✓		✓	✓		✗	✓	✓			✓	✗
Chip Seal: Single Polymer Modified	✓		✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✗		✓	✓	✗	✓	✓	✓			✓		✗	✓	✓			✓	✗
Chip Seal: Double Conventional	✓		✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✗	✓	✓	✓		✗	✓	✓		✓	✓	✓	✓	✓	
Chip Seal: Double Polymer Modified	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✗	✓		✓		✗	✓	✓		✓	✓	✓	✓	✓	
Ultra-thin Friction Course	✓		✗	✓	✓		✓	✓		✓	✓		✓	✓		✓	✓	✓	✗	✓	✓	✓			✓		✗	✓	✓		✓	✓	✓
Ultra-thin HMA Overlay	✓			✓	✓		✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓			✓		✗	✓	✓	✓	✓	✓	✓
Thin HMA Overlay	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
Thin HMA O/L & cold milling	✓				✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓			✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	

Notes: HMA = Hot-mix Asphalt, O/L = Overlay

According to Peshkin et al. [18], the expected treatment life, life extension, and unit costs of preventive maintenance treatments are summarized in Table 5. The treatment life estimates how long the treatment would last on the pavement. The life extension estimates the time it takes for the pavement to return to its current condition after application of the treatment.

Table 5. Expected Performance and Cost of Preventive Maintenance Treatments [18]

Treatment	Expected performance		Estimated Unit Cost
	Treatment Life (years)	Life Extension (years)	
1. Crack filling (non-working cracks)	2-4	N/A	\$0.10-\$1.20/ft.
2. Crack sealing (working cracks)	3-8	2-5	\$0.75-\$1.50/ft.
3. Slurry Seal	3-5	4-5	\$0.75-\$1.00/yd^2
4. Microsurfacing Single Double	 3-6 4-7	 3-5 4-6	 \$1.50-\$3.00/yd^2
5. Chip Seal Single (conventional, polymer modified) Double	 3-7 5-10	 5-6 8-10	 \$1.50-\$2.00/yd^2 \$2.00-\$4.00/yd^2
6. Ultra-thin friction course 0.4” – 0.80”	7-12	N/A	\$4.00-\$6.00/yd^2
7. Ultra-thin HMA Overlay 0.625” – 0.75”	4-8	N/A	\$2.00-\$3.00/yd^2
8. Thin HMA O/L 0.875” – 1.50” Dense Graded Open Graded (OGFC) Gap Graded (SMA)	5-12	N/A	\$3.00-\$6.00/yd^2
9. Thin HMA O/L & cold milling	5-12	N/A	\$5.00-\$10.00/yd^2

Notes: HMA = Hot-mix Asphalt, O/L = Overlay, N/A = Not Applicable

FACTORS AFFECTING TREATMENT SELECTION

There are many factors that affect preventive maintenance treatment selection specific to high traffic volume roadways outlined in the Strategic Highway Research Program (SHRP) 2 report: Guidelines for the Preservation of High-Traffic-Volume Roadways. These factors include: traffic, pavement condition, climate, work zone restrictions, expected performance, and cost [18].

Traffic level affects treatment selection in two ways. Firstly, traffic levels measure the load carried by a roadway, which affect present pavement condition and expected treatment performance. Secondly, traffic levels can limit the accessibility of a roadway for treatment applications: the higher the traffic volume, the less accessible that roadway is to maintenance activities. Traffic may also have indirect considerations based upon risk: agencies are less likely to try new treatments that may not have a long treatment life, or those which may have adverse consequences if that treatment fails [18].

Pavement condition is important to consider for treatment selection. Overall pavement condition as well as individual distress types can affect treatment selection. Preventive maintenance should be applied when pavements are in good condition. Additionally, there are certain distress types that can be addressed by preventive maintenance, however, there are some distress types for which preventive maintenance provides minimal benefit [18].

Climate affects treatment selection in two ways. Firstly, climate can affect the expected performance of a treatment. Secondly, climate can affect treatment timing. Climate can affect the curing time of certain preventive maintenance treatments. Treatments such as slurry seals require warmer temperatures to cure effectively; this treatment should therefore not be applied in cold weather since roadways would have to be closed to traffic for a relatively long time [18].

Work zone restrictions include factors such as the time available for treatment application. Most preventive maintenance treatment applications were possible during overnight or single shift applications, thus minimizing the negative effects of lane closures [18].

APPLICATION TIMING OF PREVENTIVE MAINTENANCE TREATMENTS

The National Co-Operative Highway Research Program (NCHRP) report number 523 highlights the trend of highway agencies adopting preventive maintenance policies instead of a typical worst-first approach. This document outlines a procedure to determine the optimal timing of preventive maintenance [5].

If a maintenance treatment is applied too early or too late in a pavement’s life, that treatment provides little benefit. Benefit, in this case, is defined as the difference in condition between a pavement that receives a treatment and that same pavement if no treatment was applied. Furthermore, the optimal timing of a maintenance treatment occurs not only when the greatest benefit is achieved, but when the greatest benefit is achieved at the lowest cost. As such, cost-effectiveness was incorporated into the methodology as a benefit-cost ratio in the NCHRP study [5].

The first input identified in the methodology was condition indicators. These measure pavement performance and can be monitored over time, and their value typically changes after a maintenance treatment is applied. Do-Nothing relationships were also identified as a major input since the benefit of a treatment is computed as the improvement in condition over time. The Do-Nothing relationships provide a baseline from which benefit may be calculated. Post-Treatment relationships also needed to be developed so that the increase in pavement performance due to treatment application could be estimated. Cost inputs are also an integral part of the methodology, since they allow the treatment’s cost-effectiveness to be evaluated. Different types of costs were identified in the methodology, such as preventive maintenance treatment costs, rehabilitation costs, and user delay costs. The optimal timing of treatment application was determined using the application timing with the largest benefit-cost ratio. Furthermore, to provide a more meaningful scale of cost-effectiveness, the Effectiveness Index (EI) was developed. The EI normalizes the benefit-cost ratios to a scale from 0 to 100 by comparing all benefit-cost ratios to the highest individual benefit-cost ratio. The application timing with the highest EI is selected as the optimal timing of that treatment. Expected service life of the Do-Nothing case and the Post-Treatment case are both computed in order to determine the expected extension in pavement life. The service life would be the pavement age that corresponds to the point where the pavement reaches the benefit cutoff value. These benefit cutoff values can vary between agencies, and are typically identified based on agency policies [5]. The methodology outlined in this study was integrated into a macro-enhanced Microsoft Excel spreadsheet called “OPTime”, and this is available through the NCHRP website [20].

The methodology developed in the NCHRP study was validated using four different case studies: Arizona, Kansas, Michigan, and North Carolina. In the Arizona case study, it was found that the optimal age for application of a seal coat on a Hot Mix Asphalt (HMA) pavement was 13 years. In the Kansas case study, it was found that the optimal age for application of routing and crack sealing on an HMA pavement was 11 years. In the Michigan case study, it was found that the optimal age for application of a chip seal on an HMA pavement was 11 years, while the optimal age for application of crack sealing on an HMA pavement was 5 years. In the North Carolina case study, it was found that the optimal age for application of an asphalt seal coat was 9 years [5].

Treatment selection was identified as a key step in a preventive maintenance program. Each available treatment should be outlined and compared with agency needs. Each treatment is unique and has its own benefits and their applications are limited by different constraints. As such, local or regional guidelines should be outlined for their use [5].

PERFORMANCE PREDICTION AND MODELING

Maintenance, rehabilitation, and reconstruction can impact the development of performance models. In some instances, maintenance is not recorded when applied. This would result in the development of a model that has a slower deterioration rate than would be expected if no maintenance treatments were applied. If these sections are used in the development of the performance model, there would be an overestimation of future performance. Maintenance should always be recorded so that performance models can be adjusted by either increasing condition, shifting the curve, changing the slope of the curve, or some combination of the three [15]. Many other factors limit the reliability of pavement performance models. These factors include uncertainties in pavement response to traffic and environment, quantification of factors affecting performance, and the error associated with obtaining condition data for a wide pavement area using only discrete testing points [21].

It is possible for Pavement Management Systems to contain a large number of pavement performance models based on pavement type, traffic level, region, treatment, and condition. It is sometimes useful to develop more general pavement performance models by grouping pavements that have similar characteristics [22]. Effective performance models can allow realistic predictions of future network condition and also evaluate the effectiveness of maintenance treatments [23].

As an example, the Michigan Department of Transportation (MDOT) developed a procedure to outline suitable thresholds to trigger preventive maintenance applications. MDOT uses two different indices to evaluate pavements. The first index is the distress index (DI), which measures structural deficiencies on the pavement by evaluating surface distresses. The second index is the ride quality index (RQI), which measures the functional performance of the roadway by evaluating roughness. MDOT currently makes decisions regarding maintenance and rehabilitation based on the DI. The RQI is used only after the DI trigger is reached. It is thought that roughness is directly related to acceleration of pavement deterioration since trucks travelling on significantly rough pavements can be excited, thus increasing dynamic loading on the pavement. MDOT modeled the relationship between dynamic loading (caused by RQI) and distress and thereby developed new thresholds based on the functional index, RQI. These thresholds used a more proactive approach to pavement maintenance, and promoted the application of preventive maintenance to minimize cost and extend pavement life. Light preventive maintenance was believed to have a smoothening effect on pavements, thereby reducing the RQI and, by extension, dynamic axle loading. A reliability-based model was proposed for selecting the optimal timing of preventive maintenance using the new RQI thresholds and RQI growth rates using current pavement data [24].

PREVENTIVE MAINTENANCE TREATMENT SELECTION METHODOLOGIES

There are many methods that can be used when developing a treatment selection tool. The starting point for a treatment selection tool, however, is anticipating how pavements are expected to perform over time. Pavement performance prediction and modeling is therefore a key component in a treatment selection tool. Decision tools such as decision trees or matrices, scoring systems, or optimization analysis can then aid treatment selection based on expected treatment performance.

Some agencies have developed their own approaches to development of treatment selection and general preventive maintenance strategies. The following sections provide the findings from these studies as they pertain to preventive maintenance and decision making.

Decision Trees and Matrices

For decisions being made at the project level, specific condition data must be made available [25]. As previously mentioned, factors influencing the selection of preventive maintenance treatments include type and severity of distresses, cost effectiveness of treatment, climate, etc [18].

Decision trees and decision matrices can be used for treatment selection because they can take multiple criteria into consideration. They are usually developed based upon decision processes that are already in place within the agency. They are both consistent in generation of recommendations while being flexible, allowing modification of decision criteria within the decision tree or matrix [4].

Hicks et al. [19] present a framework for selecting preventive maintenance treatments based on pavement distresses. The types of distresses considered were non load-related distresses including roughness, stable rutting, non-load-related cracking, bleeding, weathering and raveling. Decision trees are recommended for identification of appropriate treatments based on evident distresses[19].

The Maryland State Highway Administration (SHA) [26]developed a treatment selection guide for statewide preventive maintenance. This report proposes the use of decision trees along with decision matrices. There are three separate decision trees based on pavement type: flexible, composite and rigid. The flexible and composite pavement decision trees are designed to direct the user to the appropriate decision matrix based upon pavement type, ADT, and International Roughness Index (IRI). The rigid pavement decision tree identifies one decision matrix for pavements having < 25% patching; pavements with higher levels of patching require major rehabilitation or reconstruction. Use of these decision matrices requires further inputs such as condition index, friction, type of cracking, and level of rutting [26]. One of the decision trees used by Maryland SHA is shown in Figure 7. Each terminal node of the decision tree directs the user to a unique decision matrix.

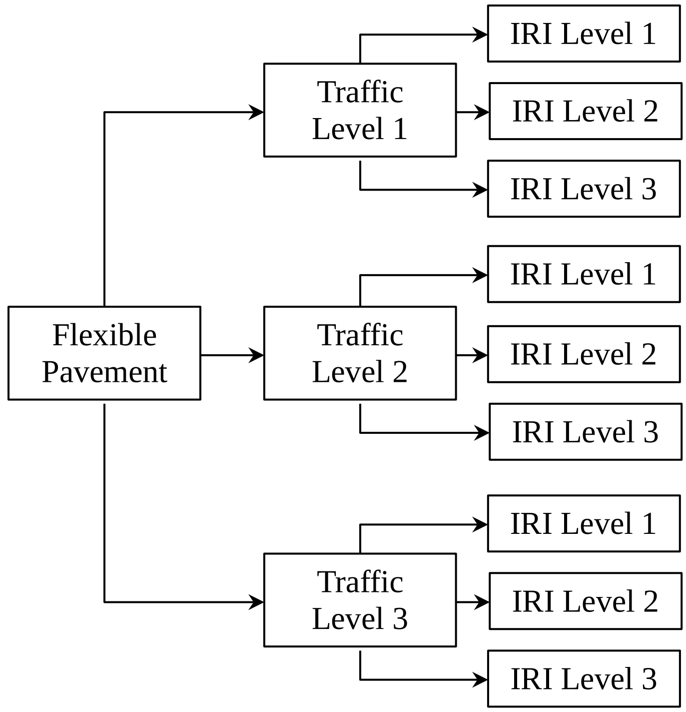


Figure 7. MDSHA Flexible Pavement Decision Tree, after [26]

Scoring Systems

In the methodology outlined by Hicks et al, the effect of each of the influential factors can be taken into account, and each factor may be assigned a weight. The treatments can then be given a score for each factor, based on its impact on the treatment. The combined weighting and scoring system can be used as a treatment selection tool [4].

A new approach to maintenance selection was developed in Egypt using the maintenance unit (MU). Instead of choosing M&R activities based on density of distresses, the MU method makes selections based on the density of localized maintenance or distress repair methods. MUs are assigned based on recommended repair type. Typically, pavements with higher values of MUs have more drastic rehabilitation needs (eg. reconstruction). It was found that this method is useful when developing a 5 year maintenance plan as it is quite accurate in developing maintenance needs [27].

Optimization

Optimization methods perform budget allocation to obtain the combination of selected pavement sections based on their benefit. Limitations of using optimization analysis for pavement selection are the difficulty in quantifying user costs and benefits of maintenance. User costs can include travel time cost, accident cost, and vehicle operating cost. Incorporating these costs can result in allocation of funds to pavements that are used the most, leading to deterioration of low-use pavements [11]. Optimization selects the most optimal solution based on maximization objectives such as pavement condition subject to budgetary constraints, or minimization objectives such as cost subject to condition constraints. Most optimization is implemented to maximize cost effectiveness at the network selection level [28].

According to Hicks et al. [19], decision trees consider distresses and traffic, however, other factors need to be taken into account when selecting the optimal treatment. Considerations should be made regarding cost, expected performance, availability of contractors, environmental impact, availability of materials, climate, etc. In the cost analysis for treatment selection, the cost-effectiveness technique is recommended over the life-cycle-cost-analysis (LCCA) approach. The LCCA will identify the treatment with the lowest cost over the analysis period, however, it does not take pavement performance into account. The cost-effectiveness analysis chooses the treatment that provides the highest performance with the lowest cost. A linear programming model was proposed which considers all factors including treatment timing, expected life, and even user delay costs.

According to Wu et al. [29], it is necessary for state departments of transportation (DOTs) to progress from historical budget allocations to needs-based allocations, and ultimately to performance-based allocations. The major shortcomings of needs-based budgeting approach for short-term preservation allocation are that districts are likely to exaggerate needs in order to secure funding, and statewide budgetary requests may not necessarily be optimal for the benefit of the entire network. A decision support model was presented to optimize short-term preservation budgeting using two operations research techniques: goal programming and analytic hierarchy process (AHP). The goal programming aspect allows for the simultaneous consideration of multiple objectives, while the AHP allows for priorities to be set for multiple criteria. The objective of the model is to maximize benefit, in terms of service life, while minimizing preservation cost. This case study shows that the proposed model is a viable option for supporting decision making [29].

An alternative to optimization methods would be the use of heuristics, which can provide “near optimal” solutions [11]. The heuristic approach calculates the marginal cost-effectiveness (MCE) or the incremental benefit-cost (IBC) and is used by numerous highway agencies [28].

The MCE approach computes the MCE for each project, and uses a series of iterations to calculate the MCE. The project with the highest MCE is selected in each iteration and replaces the project selected in the previous iteration. The MCE is calculated as shown in equation 1 [28]:

preventive maintenance or rehabilitation. A prioritization tool was developed select preventive maintenance and rehabilitation projects for each Texas highway maintenance district. The tool was developed using Microsoft Excel, and provides a user interface where the district personnel can enter the required data for each project. Default weight factors are assigned for condition score, distress score, ride score, skid number, maintenance expenditures, number of failures, age, and annual daily traffic. These default weights can be modified by the user. The tool offers four separate outputs: a rehabilitation priority list, a preventive maintenance priority list, a combined priority list, and a project scoring detail list [28].

LITERATURE REVIEW SUMMARY

Preventive maintenance is designed to keep good roads good by retarding or preventing future pavement deterioration, and should not be applied to pavements which have structural deficiencies. Preventive maintenance has been shown to have numerous benefits, including improvement of network condition at a minimum cost. Preventive maintenance treatments have the potential to extend the life of a pavement when applied correctly.

There are many preventive maintenance treatments available, and each treatment has its own benefits regarding application timing and its effectiveness at treating different distresses. Certain treatments take longer to cure, or have surface characteristics which may make them unsuitable for use on high traffic urban roads. There is also a variation between expected life extension and cost between treatments. Typically, the more expensive preventive maintenance treatments have a longer expected treatment life and are effective against more pavement distresses when compared to the less expensive treatments.

Factors affecting treatment selection include traffic level, pavement condition, distress type and severity, climate, treatment performance and cost, and work zone restrictions. These factors should be carefully considered before making a final treatment selection. Treatment placement should also occur at certain times in a pavement's life. Treatments that are applied too early or too late typically yield little benefit.

Performance models were found to be a key component of pavement management systems since they allow for prediction of future pavement condition. The reliability of these models is controlled by uncertainties to pavement response to certain factors as well as computing general pavement condition based upon discrete testing points.

There are different treatment selection methodologies available for preventive maintenance treatments. After identifying the effect of each preventive maintenance treatment, decision tools such as decision trees or matrices, scoring systems, heuristics, or optimization analysis can aid treatment selection.

Decision trees and matrices were found to be flexible enough to change decision criteria while providing a level of consistency when generating recommendations. These tools are usually developed as a way to formalize the decision process already in place in the agency. It was found that decision trees and matrices are effective when selecting feasible treatments, but did not incorporate comparison between treatments, such as cost effectiveness analysis.

Scoring systems have the ability to give different factors different weights so that they may have more influence in the decision making process. Treatment scores can also be assigned for each factor, and the highest weighted score identifies the treatment selected. Prioritization techniques can incorporate cost-effectiveness analysis to generate a list of pavement selections. Pavement sections can be ranked using cost-effectiveness, and these pavements can be selected until the budget is exhausted.

Optimization can build upon the feasible treatments that are identified using decision trees and matrices. Feasible treatments based on pavement age, traffic level, and distress type and severity can be compared based on their cost effectiveness.

Heuristic approaches are slightly more refined than ranking or prioritization, and can generate “near-optimal” solutions without using computationally exhaustive techniques such as optimization. Approaches such as the IBC or MCE are currently used in many highway agencies.

Optimization techniques are used as a decision tool to generate the best or optimal list of pavement sections which receive maintenance.

CHAPTER III – REVIEW OF CURRENT VDOT PRACTICES

INTRODUCTION

This chapter identifies and documents the current pavement preventive maintenance practices used in Virginia. It outlines the preventive maintenance treatments currently being used, general operation notes, and challenges faced in three districts (Salem, Richmond, and Northern Virginia) that are assumed to be representative of the current practices in the state.

MAINTENANCE CATEGORIES FOR THE MAINTENANCE OF ROADS IN VDOT

The total roadway system under the responsibility of the Virginia Department of Transportation is 126,186 lane miles: 5,400 lane miles of Interstate roads, 21,666 lane miles of Primary roads, 98,463 lane miles of Secondary roads, and 657 lane miles of Frontage roads [14]. Table 6 outlines the current maintenance categories used in the VDOT PMS, their expected life, and a brief description of the types of maintenance activities that are in each category.

Table 6. VDOT Maintenance Categories for Interstate and Primary roads [30]

Activity Category	Expected Life (years)	Activities
Do Nothing	N/A	N/A
Preventive Maintenance (PM)	2-5	Surface Applications: Chip Seal, Slurry Seal, Microsurfacing, Ultra thin bonded wearing course, etc.
		Crack Sealing
		Minor Patching (< 5% Pavement Area and Depth of ≤ 2”)
Corrective Maintenance (CM)	7-10	Mill and AC Overlay (≤ 2”)
		Partial Depth Patching and cover with surface treatment (< 10% Area and Depth of 4-6”)
		Partial Depth Patching and cover with Thin AC Overlay (< 10% Area and Depth of 4-6”; overlay ≤ 2”)
		Moderate Patching (< 10% Area and Depth of 6”)
Restorative Maintenance (RM)	8-12	Mill and AC Overlay (≤ 4”)
		Heavy Patching (< 20% Area, Full Depth Patch/Depth of 12”)
		Full Depth Patching with AC Overlay (< 20% Area, Full Depth Patch/ Depth of 9-12”; 4” overlay)
Rehab/Recon (RC)	15+	Mill, Break, and Seat and AC Overlay (9-12” overlay)
		Reconstruction

Note: AC – Asphalt Concrete.

Each year, pavement condition data is collected with multi-purpose data collection vehicles with cameras that take pictures of the pavement to capture cracking distresses and laser sensors which capture roughness and rutting. Pavement condition is obtained annually for Virginia’s Primary and Interstate routes and the PMS is updated with the most recent condition data. The pavement distresses that are rated include transverse cracking, longitudinal cracking, reflective transverse cracking, reflective longitudinal cracking, alligator cracking, longitudinal joint cracking, patching, potholes, delamination, bleeding, and rutting. Along with storing the individual distress data, the LDR, NDR, CCI, and IRI are calculated and stored for all sections.

Pavement types evaluated are Bituminous over Jointed Reinforced Concrete Pavement (BOJ), Bituminous over Continuously Reinforced Concrete Pavement (BOC), Bituminous Pavement (BIT), Continuously Reinforced Concrete Pavement (CRC), and Jointed Reinforced Concrete Pavement (JCP).

VDOT rates pavement deficiency using the CCI and IRI values. In both cases, 'deficient' pavements are those which are in the poor and very poor categories. The pavement condition categories based on CCI and IRI values are shown in Table 7. The statewide performance targets for interstate and primary roads are ≤ 18% deficient for condition, and < 15% deficient for IRI.

Table 7. Pavement Condition Category Based on CCI and IRI Values [14]

Pavement Condition	CCI	IRI
Excellent	90 – 100	0 – 60
Good	70 – 89	60 – 99
Fair	60 – 69	100 – 139
Poor	50 – 59	140 – 199
Very Poor	0 – 49	≥ 200

VDOT UNCONSTRAINED MAINTENANCE NEEDS

The VDOT follows a two phase process to determine pavement maintenance needs for Interstate and Primary roads, illustrated in Figure 10. The first phase uses distress data and the pavement's condition index to determine preliminary needs and expected cost. The first phase is then enhanced by a second phase, which incorporates traffic data, pavement structure, and maintenance history information to provide final needs and expected cost [30].

VDOT CCI Triggers for Preventive Maintenance

In addition to these decision matrices, preliminary treatment selection is based on CCI values. For interstate roads, pavements with a CCI value between 85 and 90 are eligible for consideration for preventive maintenance. For primary roads, pavements with a CCI between 80 and 90 are eligible for consideration for preventive maintenance [30].

VDOT Decision Matrices

There are several decision matrices used by VDOT; the specific decision matrix used for each pavement depends upon the type of distresses present and their severity and frequency. The distress types considered in these matrices are alligator cracking, transverse cracking, patching, and rutting. There are decision matrices available for pavements with only one distress type present, but there are also decision matrices available for pavements having a combination of distresses present. A sample decision matrix is shown in Table 8. The decision matrices specific to preventive maintenance selection are shown in Appendix A. Preliminary maintenance treatment selection is made after both CCI triggers and these decision matrices [30].

Table 8. VDOT Decision Matrix for Transverse Cracking [30]

Transverse Cracks per Mile				
Severity	Frequency			
	0 – 50	51 – 74	75 – 199	≥ 200
Not Severe	DN	DN	DN	PM
Severe	DN	DN	PM	CM
Very Severe	CM	RM	RC	RC

VDOT Decision Enhancements

As outlined in Figure 8, the preliminary treatment selection is enhanced using decision trees which incorporate traffic, structural condition, and maintenance history. The decision tree for preventive maintenance on interstate BIT routes is shown in Figure 9. All decision trees which affect PM selection are shown in Appendix A.

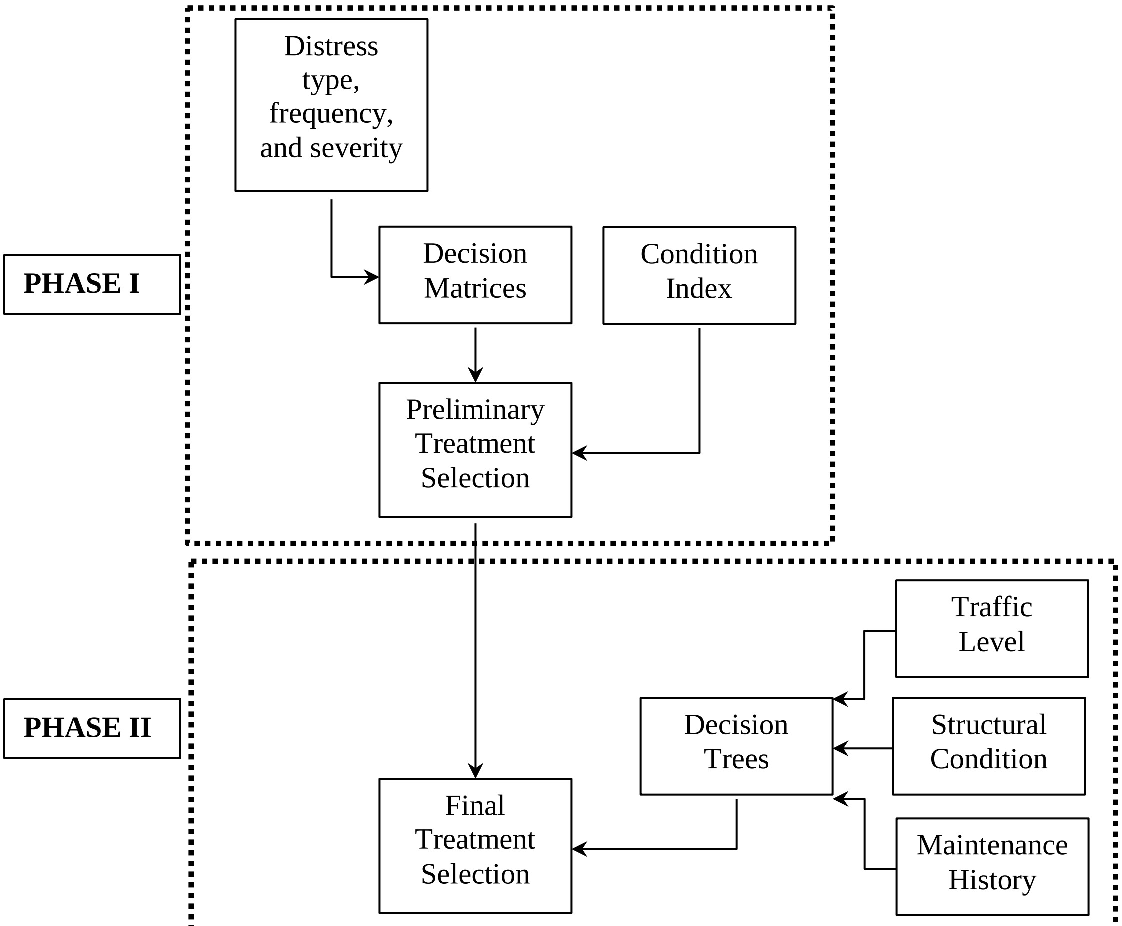


Figure 8. Process for Unconstrained Maintenance Needs Assessment [30]

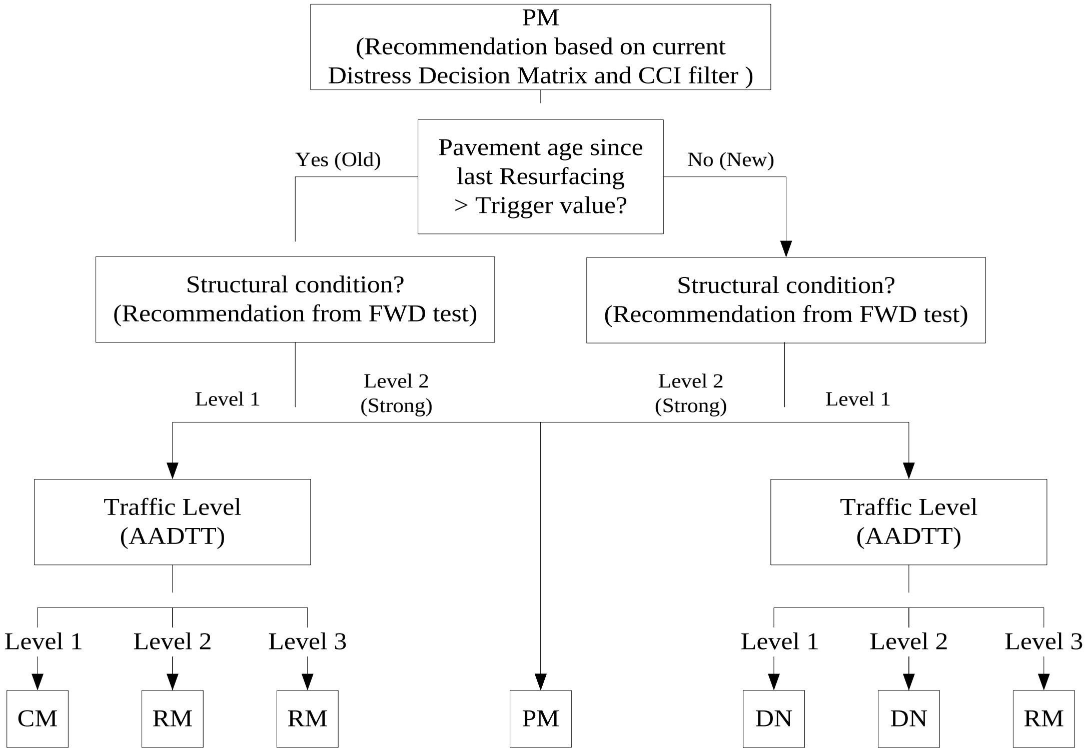


Figure 9. VDOT Decision Tree Enhancement for Preventive Maintenance on BIT Interstate Routes

VDOT Cost Estimates

The costs of different types of maintenance were calculated by the VDOT central office based on material cost bids from previous projects, adjusted for inflation. The estimated cost of each maintenance category being used by the VDOT central office is shown in Table 9.

Table 9. Preventive Maintenance Central Office Cost Estimates [30]

Treatment	Cost per Lane Mile for Interstate	Cost per Lane Mile for Primary
PM	$6,975.90	$6,977.05
CM	$71,817.50	$59,686.15
RM	$180,631.65	$153,229.45
RC	$507,958.45	$480,494.15

DISTRICT VISITS AND DOCUMENTATION OF IN-STATE PRACTICES

Three districts within Virginia were selected for evaluation: Salem, Richmond, and Northern Virginia. Maintenance and materials engineers for these regions were interviewed to identify and document the current practices within the state. These interviews allowed a comparison between state practices and the methods found in the literature and also allowed identification of preventive maintenance and pavement management policies that would be beneficial to Virginia.

Salem District

The Salem district is located in southwest Virginia. The Salem district office serves more than 650,000 citizens and 14 cities and towns within its boundaries. It serves 12 counties and has 4 residency offices. The total number of lane miles in this district is 17,966. There are 490 lane miles of interstate roadways, 2,668 lane miles of primary roads, and 14,701 lane miles of secondary roads [31]. The percent deficiency of Salem's interstate and primary road network is summarized in Table 10.

Preventive maintenance treatments are selected based on the CCI and the year the pavement was paved. Preventive maintenance is performed on road sections with CCI of 85 or higher. The data used for scheduling is obtained from the Central Office Maintenance Division in Richmond.

The interstate and primary roads are prioritized by district personnel. Secondary roads are maintained by the individual residencies. When placing chip seals, modified single seals are the typical treatment used, and this application involves the placement of two layers of aggregates. This treatment is not used on primary roads because slurry seals take too long to cure.

Table 10. Percent Deficient Interstate and Primary Roads by County [14]

County Name	% Deficient (condition)	% Deficient (ride quality)
Bedford	32.70	14.72
Botetourt	35.55	15.04
Carroll	19.88	3.94
Craig	34.70	12.90
Floyd	26.55	6.64
Franklin	38.40	6.49
Giles	26.93	6.58
Henry	15.57	4.38
Montgomery	25.18	2.50
Patrick	17.43	12.80
Pulaski	12.52	5.46
Roanoke	20.65	7.02

The typical preventive maintenance treatments currently being used in the Salem district are summarized in Table 11.

Table 11. Preventive Maintenance Treatments in Salem District

Treatment	Modifications	Placement
Chip seal	Modified single seal (#8 followed by #9)	Secondary roads < 150 vpd
Slurry seal	--	Secondary roads 150 – 200 vpd
Microsurfacing	Single application; Conventional or latex modified	Primary and Interstate
Crack Seal	--	Included on all latex schedules

Richmond District

The Richmond district is located in central Virginia. The Richmond district office serves 14 counties and the 8 cities within its boundaries. Richmond has 4 residencies. The total number of lane miles in this district is 18,562. There are 1,319 lane miles of interstate roadways, 3,417 lane miles of primary roads, and 13,750 lane miles of secondary roads [32]. The percent deficiency of Richmond's interstate and primary road network is summarized in Table 12.

Preventive maintenance is applied to roads with CCI of 75 – 85. Preventive maintenance treatments other than crack sealing are not currently used on interstate roads because most of them are structurally deficient. Like Salem district, the interstate and primary roads are maintained by district personnel, but secondary roads are maintained by residencies and subdivisions. Although fog seals are no longer used on roads, they are still used to cover rumble strips.

Table 12. Percent Deficient Interstate and Primary Roads by County [14]

County Name	% Deficient (condition)	% Deficient (ride quality)
Amelia	17.29	13.30
Brunswick	32.74	17.10
Charles City	33.28	10.07
Chesterfield	26.27	4.44
Dinwiddie	23.85	14.67
Goochland	22.04	22.32
Hanover	32.19	9.44
Henrico	30.99	26.26
Lunenburg	12.07	12.44
Mecklenburg	29.99	4.58
New Kent	39.49	3.78
Nottoway	35.32	3.84
Powhatan	44.50	3.45
Prince George	36.22	10.08

The typical preventive maintenance treatments currently being used in the Richmond district are summarized in Table 13.

Table 13. Preventive Maintenance Treatments in Richmond District

Treatment	Modifications	Placement
Chip seal	Modified single seal; double seal	Secondary roads
Slurry seal	Type B or C	Primary and Secondary roads
Microsurfacing	Latex modified, flexible	Primary roads
Crack Seal	--	Interstate
Cape Seal	--	Secondary roads

Northern Virginia (NOVA) District

The Northern Virginia district is located in the Washington DC metropolitan area. The NOVA district office supports 4 counties and 9 cities and towns located within its boundaries. The total number of lane miles in this district is 12,655. There are 684 lane miles of interstate roadways, 1,549 lane miles of primary roads, and 10,343 lane miles of secondary roads [33]. The percent deficiency of NOVA's interstate and primary road network is summarized in Table 14.

Preventive maintenance (eg. slurry seal) is applied to roads with CCI of 80-89. Preventive maintenance and corrective maintenance (eg. crack sealing and minor patching) are applied to roads with CCI of 70 – 79. The typical pavement age for application of preventive maintenance treatments is 3 – 5 years for high volume roads and 5 – 10 years for low volume roads. Interstate, primary, and secondary roads are all handled by the district personnel. The one exception is Arlington County, which maintains its secondary roads.

Some challenges identified were funding and traffic level. Budgetary constraints limit the range of treatments that can be applied to these pavements. Furthermore, the district's heavy traffic volumes place extra strain on maintenance applications: the conditions deteriorate very rapidly, making scheduling more difficult.

Table 14. Percent Deficient Interstate and Primary Roads by County [14]

County Name	% Deficient (condition)	% Deficient (ride quality)
Arlington	45.41	49.88
Fairfax	38.22	26.82
Loudon	50.30	13.71
Prince William	24.46	9.14

The typical preventive maintenance treatments currently being used in the Northern Virginia district are summarized in Table 15.

Table 15. Preventive Maintenance Treatments in NOVA District

Treatment	Modifications	Placement
Slurry seal	Type A, B, C, double seal modified, latex	Primary and Secondary roads
Crack Seal	--	Included on all latex schedules
Cape Seal	--	Application to start in 2013

General Observations

A comparison of treatment placement across districts is shown in Table 16. The CCI triggers for preventive maintenance are shown in Table 17.

Table 16. Treatment Placement by District

Treatment	Placement in district		
	Salem	Richmond	NOVA
Crack Seal	Primary and Interstate	Interstate	Primary and Secondary Roads
Slurry Seal	Secondary Roads (150 - 200 vpd)	Primary and Secondary Roads	Primary and Secondary Roads
Microsurfacing	Primary and Interstate	Primary Roads	--
Chip Seal	Secondary Roads (<150 vpd)	Secondary Roads	--
Cape Seal	--	Secondary Roads	--

Table 17. CCI Triggers by District

District	CCI Triggers for PM
Salem	85 – 100
Richmond	75 – 85
NOVA	80 – 89

The recommendations provided by the VDOT central office follow a methodology that is inherent in their PMS. These are recommendations for general maintenance categories, however, and districts must select the specific treatment types and which pavement sections should be selected based on their experience and judgment. After reviewing the responses received from the Salem, Richmond, and NOVA districts, it was found that each district developed its own preventive maintenance policy over time. Each district has different criteria for placement of these preventive maintenance treatments. For example, slurry seals are placed on primary and secondary roads in Richmond and NOVA, but only on secondary roads in Salem. Microsurfacing is used on interstate and primary roads in Salem, but only on primary roads in Richmond. NOVA applies slurry seals to primary and secondary roads, but does not use microsurfacing. Additionally, the CCI triggers for preventive maintenance vary between districts.

This district investigation highlighted the need for a formal preventive maintenance policy that builds upon the central office recommendations using distress type and severity, pavement age, network classification, and traffic to develop preventive maintenance treatment selections that are consistent across districts. The findings from the district investigations were compiled as a report and submitted to the Virginia Department of Transportation [34].

CHAPTER IV–RECOMMENDATIONS FOR IMPLEMENTATION OF A PREVENTIVE MAINTENANCE POLICY

Currently, each district uses different criteria for selecting pavements which receive preventive maintenance. The PMS uses decision matrices and decision trees along with CCI triggers to assign maintenance categories to each section. It is recommended that the decision matrix analysis results obtained from the PMS be used in district selection.

The effectiveness of each treatment for specific distress types was obtained from the literature. It was determined that chip seals and slurry seals in general were not appropriate for use on interstate pavements. Chip seals have an aggregate cover that may become dislodged with traffic traveling at high speeds [17]. Slurry seals depend on climatic conditions to break and cure, and their curing time is highly unpredictable [18]. Since lane closures on interstate pavements should be minimized, it was decided that slurry seals should not be applied in these cases. The treatment feasibility for the treatments specific to this thesis were selected based on the pavement age, traffic level, and the distresses used in the VDOT decision matrices: alligator cracking, transverse cracking, rutting, and patching. The treatment characteristics were based on those found in the literature review, and these are listed in Table 18. The expected treatment life and cost of each treatment from the most recent SHRP 2 study [18], are presented in Table 19 along with current unit costs obtained directly from VDOT.

Table 18. Treatment Feasibility.

Treatment	Type of Network	Age		Traffic Level	Alligator Cracking Severity	Transverse Cracking Severity	Rutting Severity	Patching Severity
		Min	Max					
Chip Seal	Primary	5	8	All	1	1	1	1
Slurry Seal	Primary	5	8	Low & Medium	1	1	--	--
Microsurfacing	Primary, Interstate	5	8	All	1	1	1	1
THMACO	Primary, Interstate	6	12	All	1, 2	1, 2	1	1

Table 19. Treatment Life and Estimated Cost [18]

Treatment	Treatment Life (years)	SHRP 2 Estimated Unit Cost (per lane mile)	VDOT Unit Cost (per lane mile)
Chip Seal	3-7	$10,771.20 -$13,939.20	$ 8,839.00
Slurry Seal	3-5	$5,068.80 -$ 6,969.60	$13,376.00
Microsurfacing	3-6	$10,771.20 -$20,908.80	$16,620.00
THMACO	5-12	$20,908.80 -$42,451.20	$33,077.00

An approach combining expected performance, decision matrix analysis, cost effectiveness, and heuristics was deemed to be the most beneficial for implementation of a preventive maintenance policy in Virginia. Multiple levels of analysis led to the development of a robust decision making tool.

It is recommended that the district engineers obtain a list of pavements from the PMS which satisfy VDOT requirements for application of preventive maintenance. A quick reference guide was prepared for use at the district level to facilitate the execution of this step.

The treatment selection tool was developed in two parts: feasible treatment identification and the district-wide selection. The framework of the treatment selection tool is presented in Figure 10.

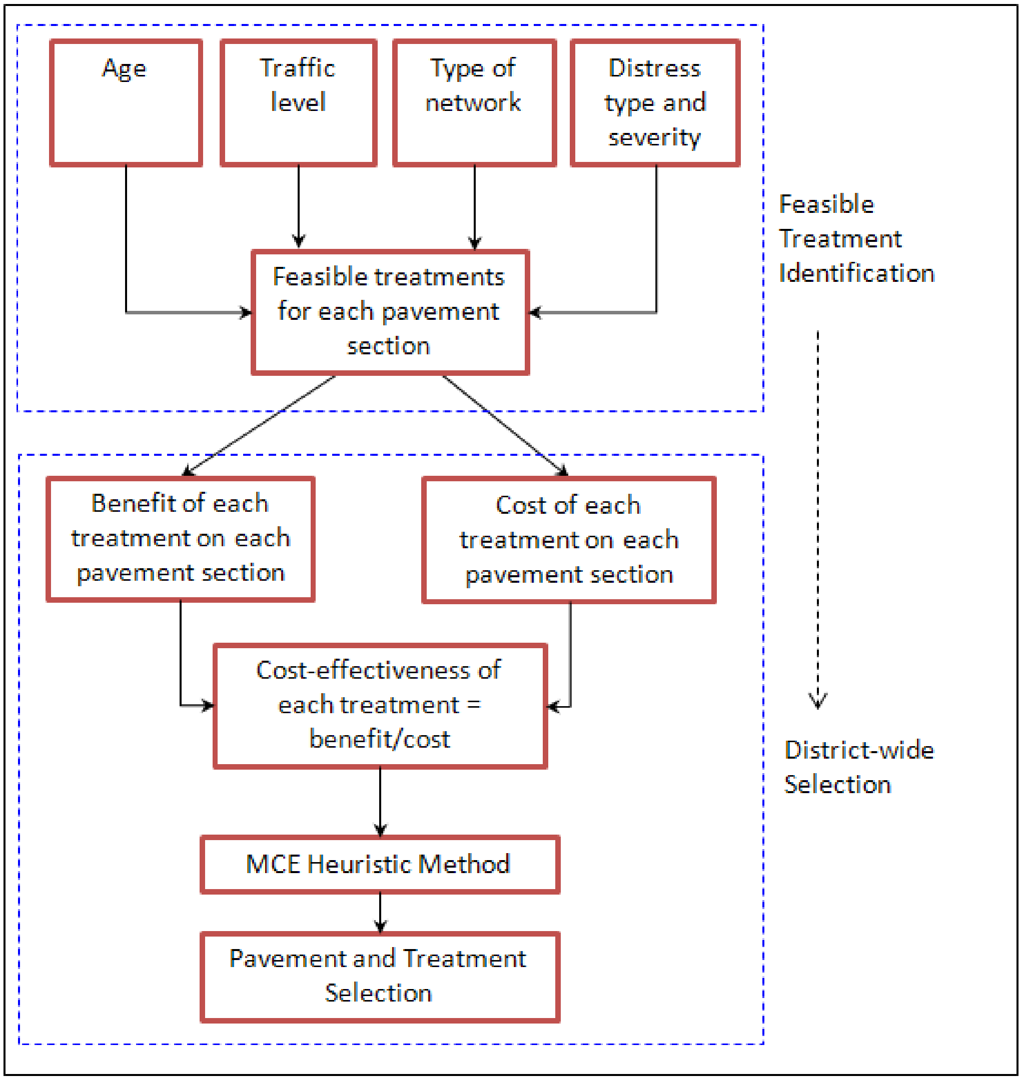


Figure 10. Overview of Treatment Selection Tool

Firstly, the treatment feasibility is established based on the pavement section's age, traffic level, type of network, and distress type and severity. Next, the benefit of each treatment on each section was calculated. The benefit was calculated as the product of lane miles and the area between the DN and PM curves above a specified benefit cutoff value, shown in Figure 11. This benefit cutoff value was assumed to be 60 based on the VDOT deficient pavement criterion; pavements that have a CCI below 60 are considered to be deficient.

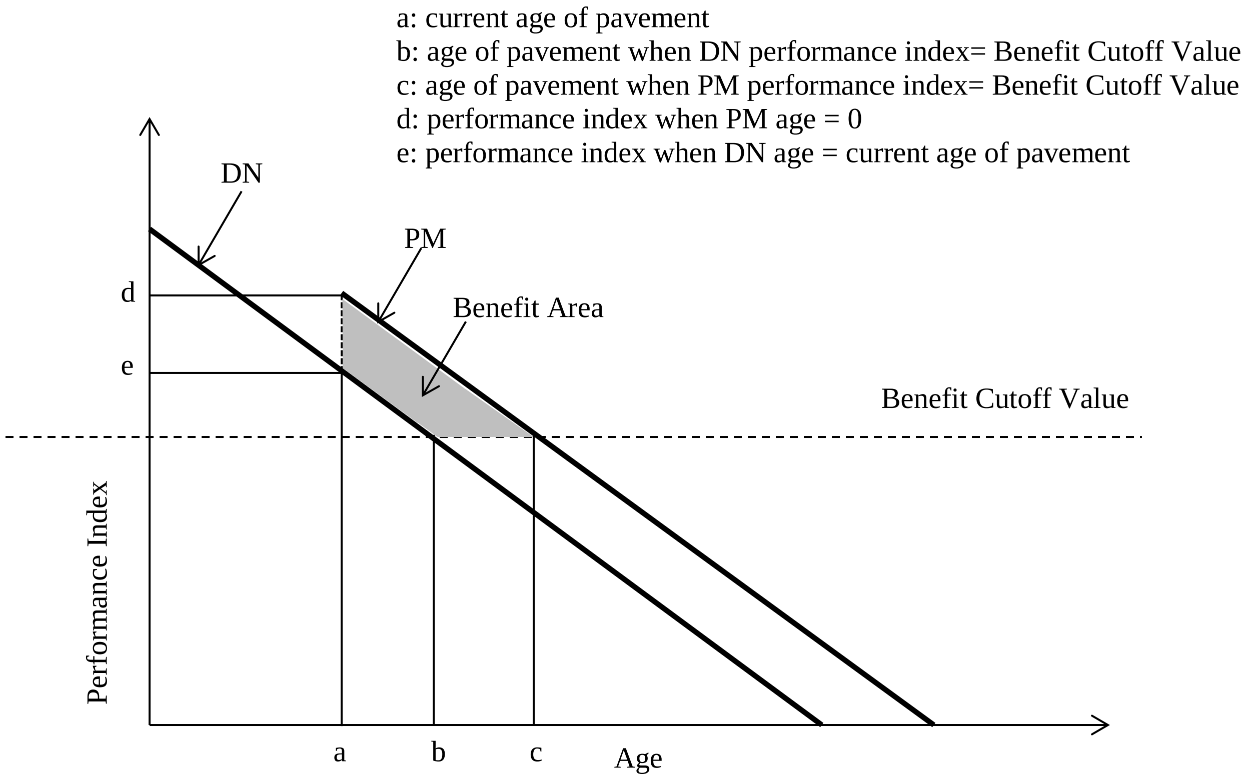


Figure 11. Computation of Treatment Benefit

The cost of each treatment on each maintenance section is calculated using specified unit costs and pavement area as shown in equation 3:

that section is removed. This adjustment is made because there would be a higher benefit achieved even though the cost may have been slightly higher.

These recommendations can greatly benefit engineers at the districts to ensure that near-optimal decisions are being made regarding preventive maintenance.

CHAPTER V – DEVELOPMENT OF TREATMENT SELECTION TOOL

This chapter outlines the development of the treatment selection tool that was completed as a part of this thesis. The tool required certain user inputs in order to develop recommendations for treatment selection on each section, and to provide a prioritized list of pavements that can be used by the districts to aid in their maintenance activities. The user inputs required for the tool are:

- Treatment performance
- Do-Nothing performance
- Current-year condition data
- Cost data
- Central Office recommendations for total preventive maintenance lane miles and budget specific to each district.

The treatment feasibility identified in Chapter IV was incorporated into the tool. Also, the user is given a choice to either use default do-nothing and treatment performance models as developed in this thesis, or to input new models. All inputs required for the tool are outlined in the following sections.

TREATMENT PERFORMANCE DATA ANALYSIS

Pavement condition data was obtained from the VDOT PMS to develop treatment performance models for preventive maintenance on BIT. The performance of four preventive maintenance treatments were considered based on condition data obtained for interstate and primary systems in Virginia for: chip seals, slurry seals, microsurfacing, and THMACO.

Linear regression was used in this thesis for performance curve development. The linear model allows for a general computation of benefit with minimal reduction in the accuracy provided by more complex models. As an example figure, a quick comparison between a VDOT model and a linear model is presented in Figure 12. This comparison shows that the linear model is an adequate representation of expected pavement performance expressed by the VDOT model.

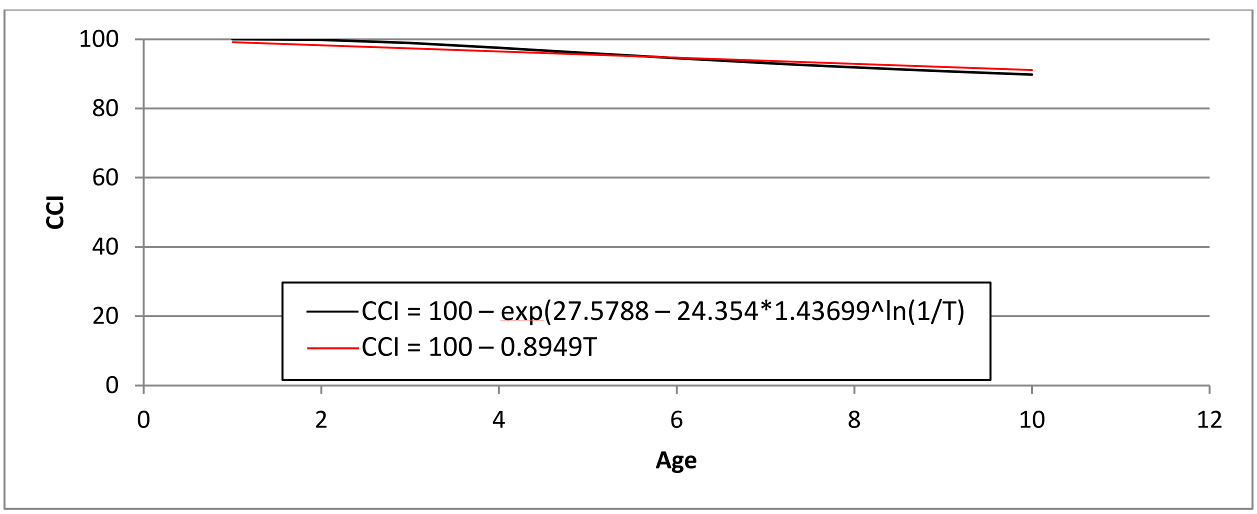


Figure 12. Comparison between VDOT Model and Linear Model

Microsurfacing had the largest dataset with 1,363 records available. There were 362 records available for slurry seal, 63 records available for chip seal, and 22 records available for THMACO.

Some sections had CCI values of -1, suggesting that the data for these sections was not collected. These null sections were removed. After inspecting the data, it was seen that pavement condition seemed to increase after 10 years. This was attributed to the possibility of treatments being applied to pavements without being recorded. Pavements older than 10 years were therefore not considered in the analysis.

Since the microsurfacing dataset was so large, this data was divided according to type of network: interstate or primary.

Based on recommendations from VDOT central office personnel, an outlier analysis was performed to remove any outliers in the data. Data was grouped according to pavement age, and the standard deviation and average condition was computed for each group. Any pavement section having ($z < -1.96$, $z > 1.96$) was removed from the analysis. Linear regression was then performed to obtain the expected performance of each preventive maintenance treatment. The results of the analysis are presented in Figure 13 to Figure 17. A summary of all the models developed is listed in Table 20.

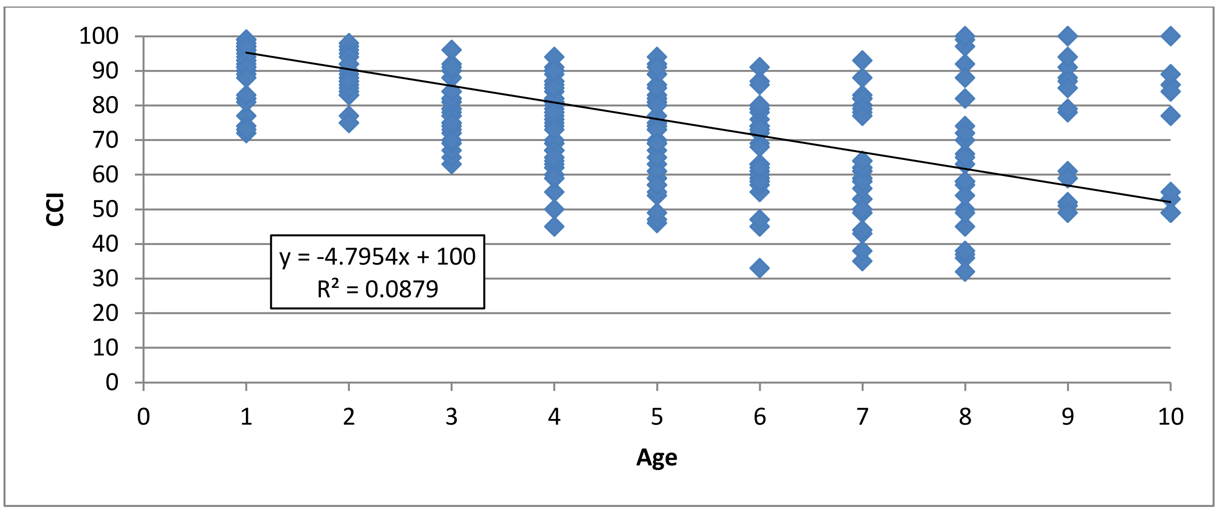


Figure 13. CCI versus Age for Microsurfacing on Interstate Pavements

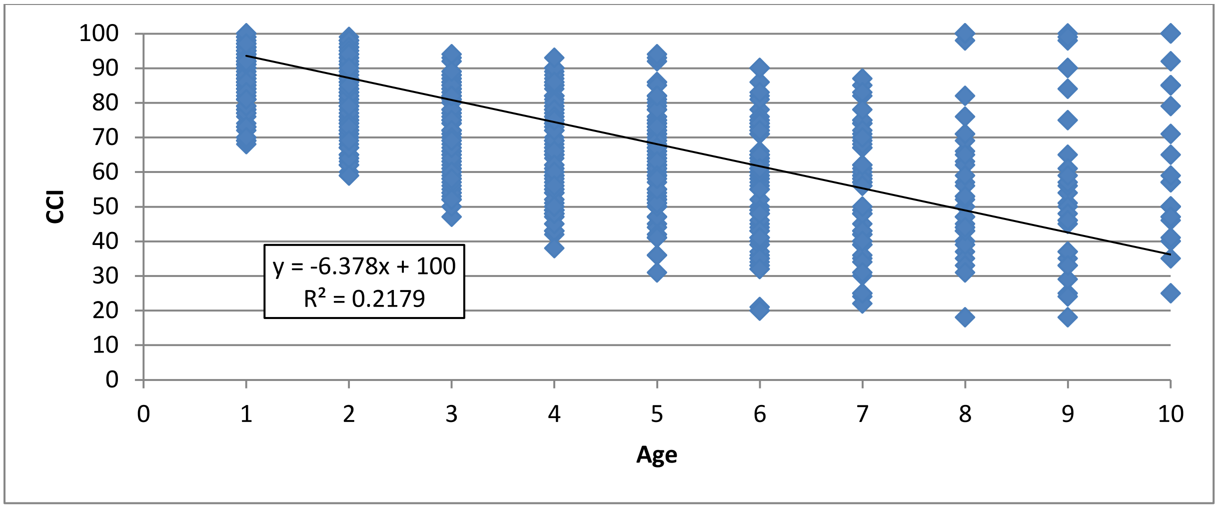


Figure 14. CCI versus Age for Microsurfacing on Primary Pavements

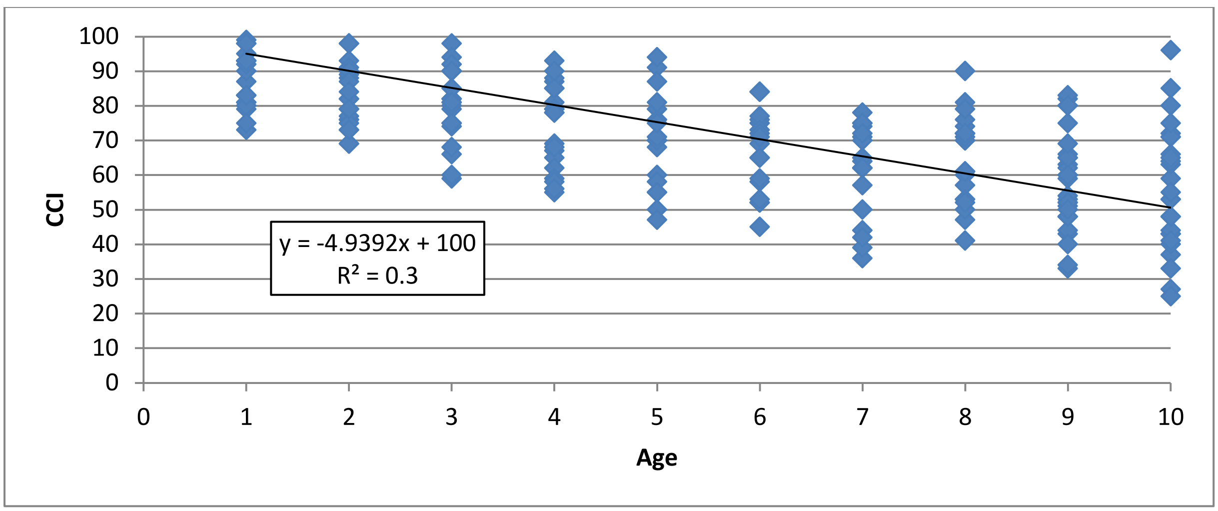


Figure 15. CCI versus Age for Slurry Seal

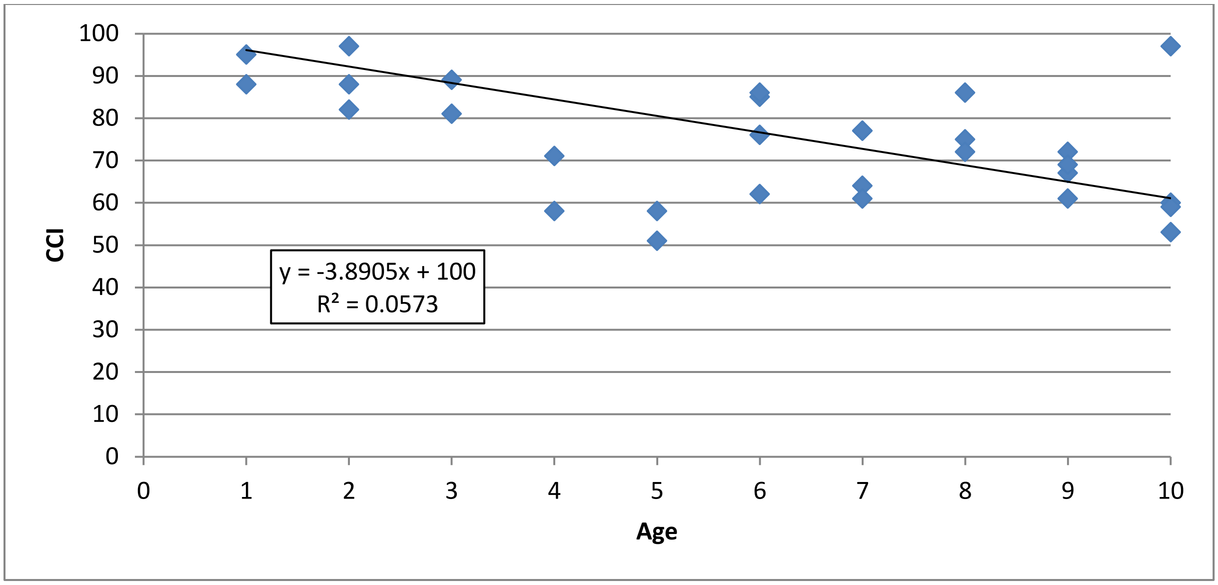


Figure 16. CCI versus Age for Chip Seal

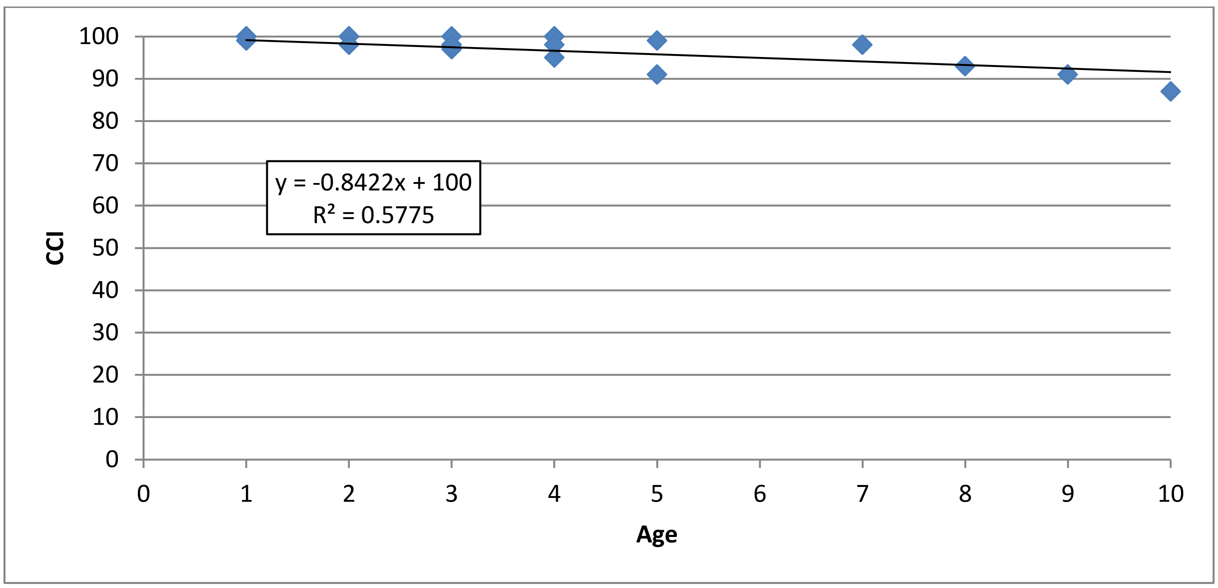


Figure 17. CCI versus Age for THMACO

Table 20. PM Treatment Models

PM Treatment	Model	R^2
Microsurfacing Interstate	CCI = – 4.7954*Age + 100	0.0879
Microsurfacing Primary	CCI = – 6.3780*Age + 100	0.2179
Slurry Seal	CCI = – 4.9392*Age + 100	0.3000
Chip Seal	CCI = – 3.8905*Age + 100	0.0573
THMACO	CCI = – 0.8422*Age + 100	0.5775

The models developed as part of this analysis were counterintuitive. Microsurfacing is expected to perform better than slurry seals because higher quality aggregates are used, as well as a polymer-modified asphalt emulsion. The models showed that the rate of deterioration for microsurfacing on primary routes was much faster than the rate of deterioration of slurry seals. It is believed that microsurfacing was applied to pavements that were in poor condition, thus rendering the treatment ineffective.

These sections could not be identified because the condition data before treatment application was not easily available. Most condition data for sections before treatment application was unavailable because sections changed with new treatment applications. This is illustrated in Figure 18. It is recommended that district personnel who are familiar with the general condition of certain pavement sections identify those sections that were in poor condition before preventive maintenance was applied.

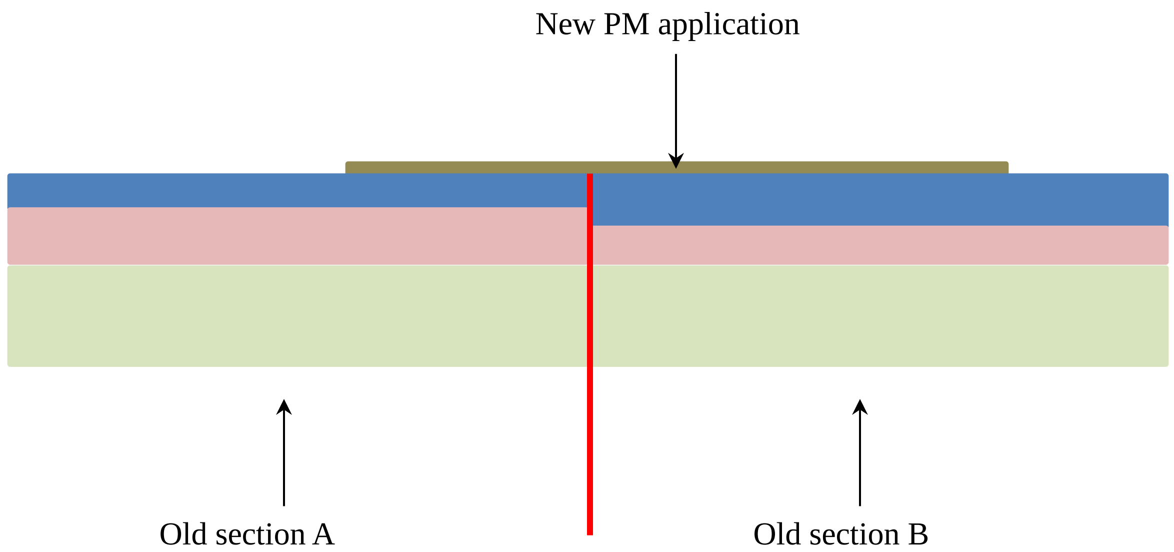


Figure 18. Section Change with PM Application

Sections with atypical performance needed to be removed from the analysis. In certain cases, maintenance activities are not input into the PMS. In these situations, there is an increase in section performance with no recorded maintenance activities. In some cases, these sections were identified using the outlier analysis. However, it is believed that there are many other sections that were not identified in the outlier analysis. It is recommended that district personnel who are familiar with the specific pavement maintenance history for their district update these maintenance activities in the PMS.

It is believed that when the data for maintenance history is updated and the pavements that have known structural issues are removed from the analysis, the reliability of the models would be improved. The models developed as part of this thesis were used in the selection tool; however, it is recommended that these models are refined over time so that the performance of these preventive maintenance treatments can be better estimated.

The selection tool gives the user the option to input new do nothing models and treatment performance models. The model selection window for primary routes is shown in Figure 19.

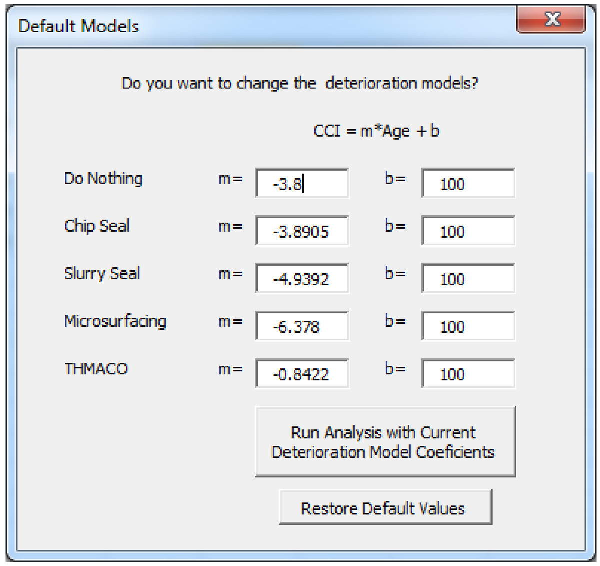


Figure 19. Model Selection Window

DO NOTHING MODELS

The do nothing models were then retrieved from the PMS. Models were available for each type of pavement (BIT, BOC, BOJ, CRC, JRC), each classification of pavement (Interstate, Primary), and each type of last performed maintenance (CM, RM, RC). For the PMS analysis, the default model assigned to pavement sections is the CM model. A linear approximation of the model was obtained for Interstate and Primary routes on BIT. These linear do-nothing models are expressed in equation 5 for interstate routes and equation 6 for primary routes.

$$CCI = -5.20 * Age + 100 \quad \text{(eq. 5)}$$

$$CCI = -3.80 * Age + 100 \quad \text{(eq. 6)}$$

CURRENT YEAR CONDITION

The current year pavement condition needed to be obtained from the PMS for each district. Eligible candidates for preliminary consideration for preventive maintenance included all pavements that satisfied PMS requirements for PM. The results from the PMS decision matrix analysis were obtained for all sections recommended for PM on BIT pavements. After exporting this data from the PMS and saving it in a spreadsheet, it was then imported into the treatment selection tool. The data import window for primary pavements is shown in Figure 20.

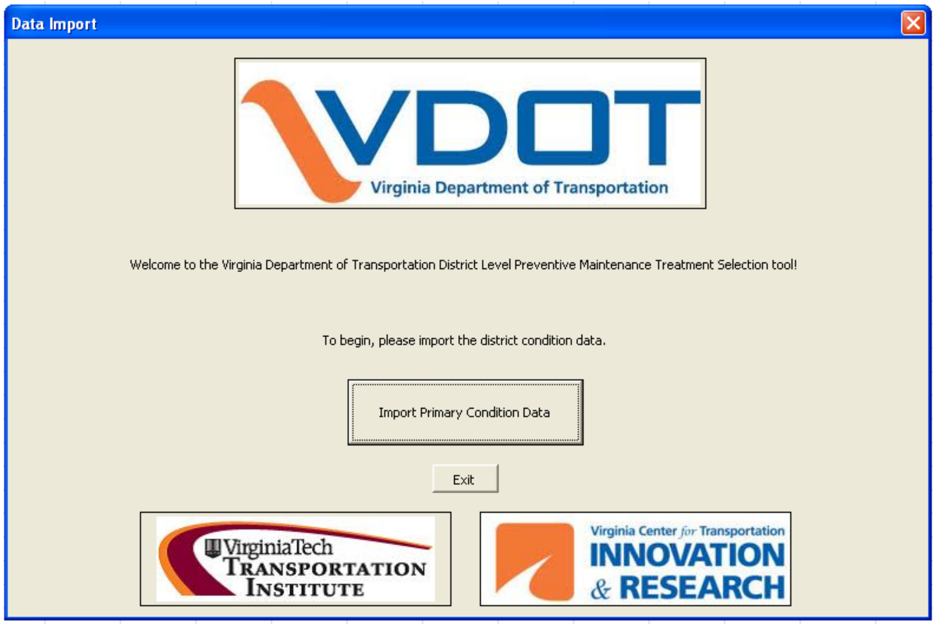


Figure 20. Data Import Window

COST

Approximate values for treatment costs calculated using values obtained from the literature review. These values were input into the treatment selection tool. The unit cost for each treatment is shown in Table 21.

Table 21. Treatment Costs

Treatment	Cost per Lane Mile
Chip Seal	$ 8,839.00
Slurry Seal	$13,376.00
Microsurfacing	$16,620.00
THMACO	$33,077.00

The selection tool gives the user the option to input new cost data based on local market prices. This flexibility is particularly useful since treatment costs vary between districts and over time. The unit cost input window is shown in Figure 21. This window is automatically populated with default model values. Users have the option to change these values, and if so, restore the default values if they see fit.

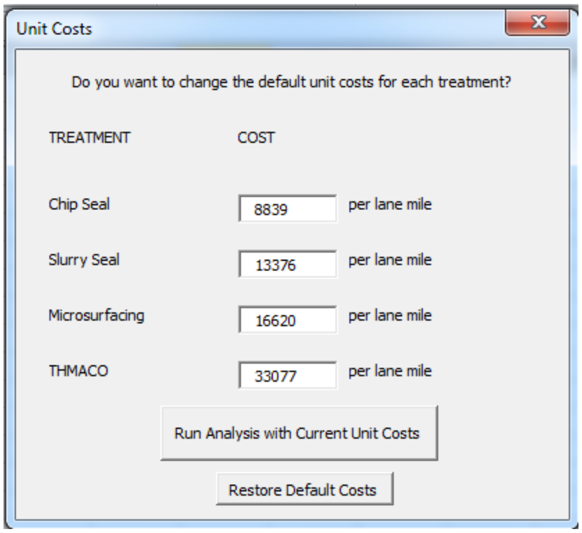


Figure 21. Unit Cost Input Window

CENTRAL OFFICE RECOMMENDATIONS

The VDOT Central Office provides recommendations for each district regarding recommended lane miles for each maintenance type (DN, PM, CM, RM, RC) and the budget available for these recommendations. The selection tool gives the user the ability to input these Central Office recommendations based on the district being considered in the analysis. The Central Office recommendations window is shown in Figure 22.

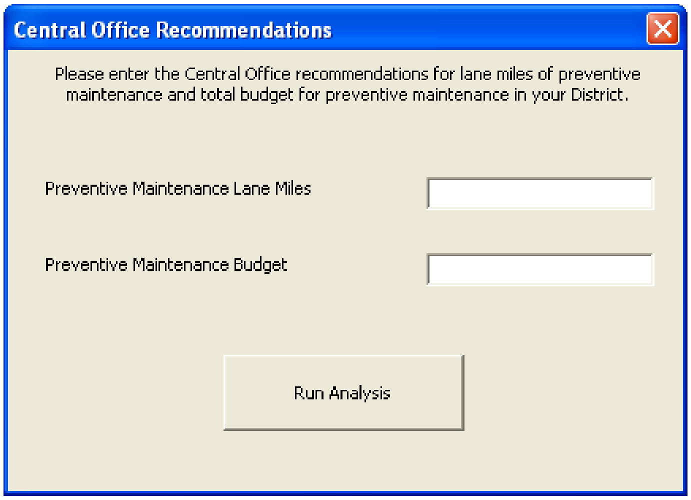


Figure 22. Central Office Recommendations Window

DISTRICT-WIDE SELECTION

The procedure outlined in Chapter IV was integrated into the selection tool. Computations were automated, and the tool provided output regarding all possible feasible treatments, the cost effectiveness of treatments, and the pavement and treatment selections for the district based on the MCE computations. Examples of these outputs are presented in the following section.

RESULTS AND ANALYSIS

The treatment selection tool was run for each district and each roadway classification (Interstate and Primary) to obtain a prioritized list of pavement sections and their respective treatments.

If a treatment was identified as being feasible for application on a pavement section, it was assigned a value of "Y". If a treatment was not feasible, it was assigned a value of "N". An example of the treatment feasibility output is presented in Figure 23.

Section Number	Chip Seal	Slurry Seal	Microsurfacing	THMACO
1	Y	Y	Y	Y
2	Y	N	Y	Y
3	Y	Y	Y	Y
4	Y	Y	Y	Y
5	Y	Y	Y	Y
6	Y	N	Y	Y
7	Y	Y	Y	Y
8	Y	Y	Y	Y
9	N	N	N	Y

Figure 23. Treatment Feasibility

As part of the MCE methodology, the benefit and cost were then computed for each feasible treatment on each pavement section. An example of the benefit and cost output is presented in Figure 24.

Section Number	Chip Seal Benefit	Slurry Seal Benefit	Microsurfacing Benefit	THMACO Benefit	Chip Seal Cost	Slurry Seal Cost	Microsurfacing Cost	THMACO Cost
1	202.961	32.96551	24.92706785	206.309	1944.58	2942.72	3656.4	7276.94
2	202.476		29.459262	243.819	2298.14		4321.2	8600.02
3	193.173	39.37383	27.68155323	291.509	2828.48	4280.32	5318.4	10584.6
4	201.506	50.9467	38.52365031	318.841	3005.26	4547.84	5650.8	11246.2
5	193.343	71.93848	52.93852401	481.659	4596.28	6955.52	8642.4	17200
6	192.398		57.01071816	518.709	4949.84		9307.2	18523.1
7	182.273	73.82594	51.90291231	546.58	5303.4	8025.6	9972	19846.2
8	182.273	73.82594	51.90291231	546.58	5303.4	8025.6	9972	19846.2
9				892.499				31092.4

Figure 24. Treatment Benefit and Cost

Each combination of pavement section and feasible treatment was then listed. The treatments were then sorted in ascending order based on their cost. The Benefit/Cost ratios were computed for each combination, and the increase in cost and increase in benefit were both computed for each new treatment on each section. Any treatments that had an increase in cost but a decrease in benefit were removed from consideration for that section. An example of this output is presented in Figure 25.

Section Number	Treatment	Benefit	Cost	Benefit/cost	Incremental Cost dC	Incremental Benefit dB
1	Chip Seal	202.96	1944.58	0.1043728	1944.58	202.961307
1	THMACO	206.31	7276.94	0.028351	5332.36	3.347393628
2	Chip Seal	202.48	2298.14	0.0881044	2298.14	202.4762544
2	THMACO	243.82	8600.02	0.028351	6301.88	41.34311911
3	Chip Seal	193.17	2828.48	0.0682956	2828.48	193.1726755
3	THMACO	291.51	10584.6	0.0275408	7756.16	98.33670733
4	Chip Seal	201.51	3005.26	0.0670512	3005.26	201.5061491
4	THMACO	318.84	11246.2	0.028351	8240.92	117.3345701
5	Chip Seal	193.34	4596.28	0.0420652	4596.28	193.3434123
5	THMACO	481.66	17200	0.0280034	12603.76	288.3153347
6	Chip Seal	192.4	4949.84	0.0388696	4949.84	192.3983597
6	THMACO	518.71	18523.1	0.0280034	13573.28	326.3110602
7	Chip Seal	182.27	5303.4	0.0343691	5303.4	182.273307
7	THMACO	546.58	19846.2	0.0275408	14542.8	364.3067857
8	Chip Seal	182.27	5303.4	0.0343691	5303.4	182.273307
8	THMACO	546.58	19846.2	0.0275408	14542.8	364.3067857
9	THMACO	892.5	31092.4	0.0287047	31092.38	892.498812

Figure 25. Benefit Cost Ratio, Incremental Cost, and Incremental Benefit

The MCE was computed as the change in benefit divided by the change in cost. The corrected MCE was calculated as stated in equation 7. An example of the MCE and corrected MCE output is shown in Figure 26.

$$MCE_{corrected} = \min(BCR, MCE) \quad \text{(eq. 7)}$$

Section Number	Treatment	Incremental Cost dC	Incremental Benefit dB	dB/dC	Corrected dB/dC
1	Chip Seal	1944.58	202.961307	0.10437	0.10437
1	THMACO	5332.36	3.347393628	0.00063	0.00063
2	Chip Seal	2298.14	202.4762544	0.0881	0.0881
2	THMACO	6301.88	41.34311911	0.00656	0.00656
3	Chip Seal	2828.48	193.1726755	0.0683	0.0683
3	THMACO	7756.16	98.33670733	0.01268	0.01268
4	Chip Seal	3005.26	201.5061491	0.06705	0.06705
4	THMACO	8240.92	117.3345701	0.01424	0.01424
5	Chip Seal	4596.28	193.3434123	0.04207	0.04207
5	THMACO	12603.76	288.3153347	0.02288	0.02288
6	Chip Seal	4949.84	192.3983597	0.03887	0.03887
6	THMACO	13573.28	326.3110602	0.02404	0.02404
7	Chip Seal	5303.4	182.273307	0.03437	0.03437
7	THMACO	14542.8	364.3067857	0.02505	0.02505
8	Chip Seal	5303.4	182.273307	0.03437	0.03437
8	THMACO	14542.8	364.3067857	0.02505	0.02505
9	THMACO	31092.38	892.498812	0.0287	0.0287

Figure 26. MCE and Corrected MCE

The list was then sorted in descending order of corrected MCE values: combinations. Sections were then selected until the budget was exhausted. While making selections, if there was any new treatment for a section on the list, this treatment was selected for that section and the previous selection for that section was removed. An example of this process is presented in Figure 27. The duplicate column was used to check whether or not the section had a prior treatment recommendation.

Section Number	Treatment	Corrected dB/dC	Cumulative Cost	Duplicate
1	Chip Seal	0.104372824	1944.58	0
2	Chip Seal	0.088104404	4242.72	0
3	Chip Seal	0.068295578	7071.2	0
4	Chip Seal	0.067051153	10076.46	0
5	Chip Seal	0.042065195	14672.74	0
6	Chip Seal	0.038869612	19622.58	0
7	Chip Seal	0.034369142	24925.98	0
8	Chip Seal	0.034369142	30229.38	0
9	THMACO	0.028704744	61321.76	0

Figure 27. Corrected MCE and Cumulative Cost

There were two main treatments that were recommended by the selection tool: chip seal and THMACO. After reviewing the models that were developed in this chapter, it was seen that these two treatments had the slowest expected rate of pavement deterioration when compared to slurry seal and microsurfacing. There were considerably less data points for chip seal and THMACO than there were for slurry seal and microsurfacing. The limited sample of pavements that received these treatments had a relatively good response to these treatments. The slurry seal and microsurfacing treatments had a much larger dataset, and there was a high level of variability within the data. It is important to note that the potential benefit of these treatments was not represented by these models, and a comprehensive data review is recommended to be carried out at the district level.

A summary of the analysis results as compared to the targets set by the central office is shown in Figure 28 and Figure 29.

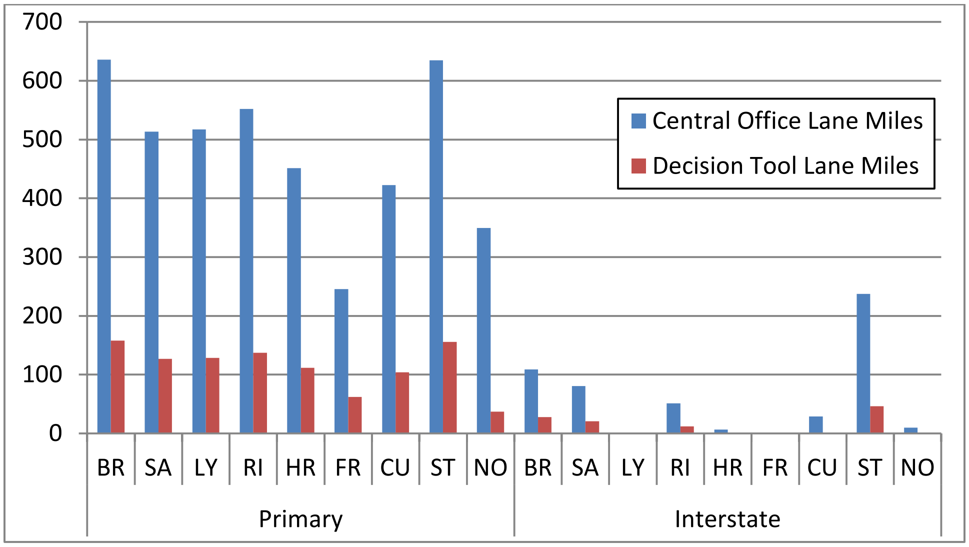


Figure 28. Target Lane Miles and Recommended Lane Miles by District and Pavement Classification

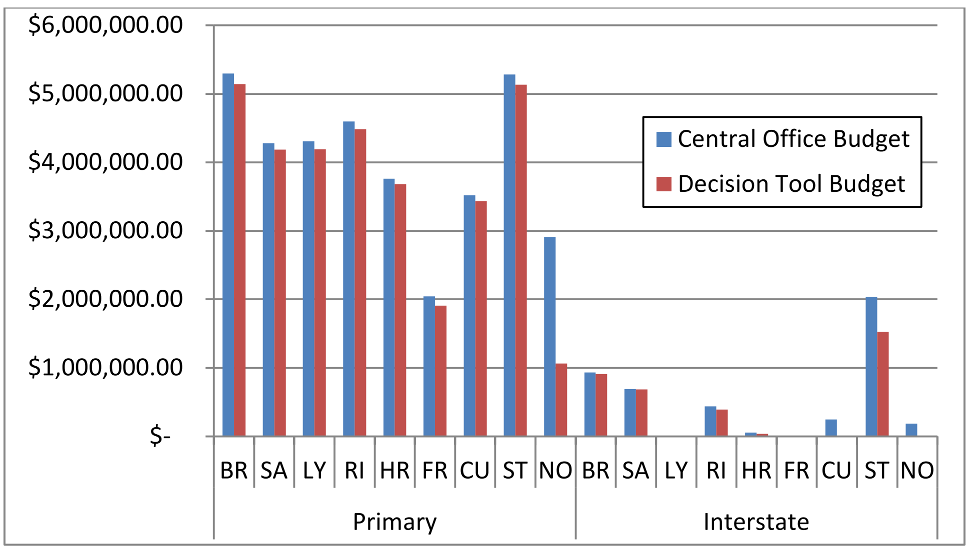


Figure 29. Target Budget and Recommended Budget by District and Pavement Classification

In cases where the decision tool budget recommendations were significantly lower than the central office budget, there were insufficient sections that were recommended for preventive maintenance. In these cases, the pavement age was either too low or too high.

The expected cost per lane mile of the preventive maintenance category is computed as a weighted average of the lowest bid prices from the previous year, adjusted for inflation. The preventive maintenance treatments most frequently used in Virginia are currently crack sealing and patching. The weighted estimate of preventive maintenance developed by the central office therefore does not reflect the cost of surface applications such as the four treatments identified in this thesis.

After comparing the calculated treatment costs for each pavement section in the analysis to the expected cost for each treatment based on the PMS computations, it was seen that the cost for the preventive maintenance category was approximately equal to the cost of chip seal. For pavements that were assigned THMACO, the calculated treatment costs were approximately four times higher than the cost for the preventive maintenance category. Based on the expected performance, in most cases, THMACO yielded the highest benefit and THMACO was therefore assigned to most sections. Since the cost of a THMACO is almost four times the expected cost of the preventive maintenance treatment category, only about one quarter of the recommended lane miles were selected for maintenance.

VERIFICATION

The results obtained using the MCE method for Bristol interstate routes were compared to a true optimization method using an integer program outlined in equations 8 through 15.

$\text{Max } z = \sum x_i b_i / c_i$ (eq. 8)

Subject to

$\sum x_i c_i \leq p$ (eq. 9)

$\sum x_i l_i \leq q$ (eq. 10)

$x_i = 1$ if section i is selected; 0 otherwise (eq. 11)

Where

b_i = benefit of section i (eq. 12)

c_i = cost of section i (eq. 13)

p = recommended budget for PM (eq. 14)

q = recommended lane miles for PM (eq. 15)

The integer program was set up in Microsoft Excel and the Solver Add-in was used to determine an optimal solution. A comparison of the results of the MCE method and the integer program solution are shown in Figure 30 and Figure 31.

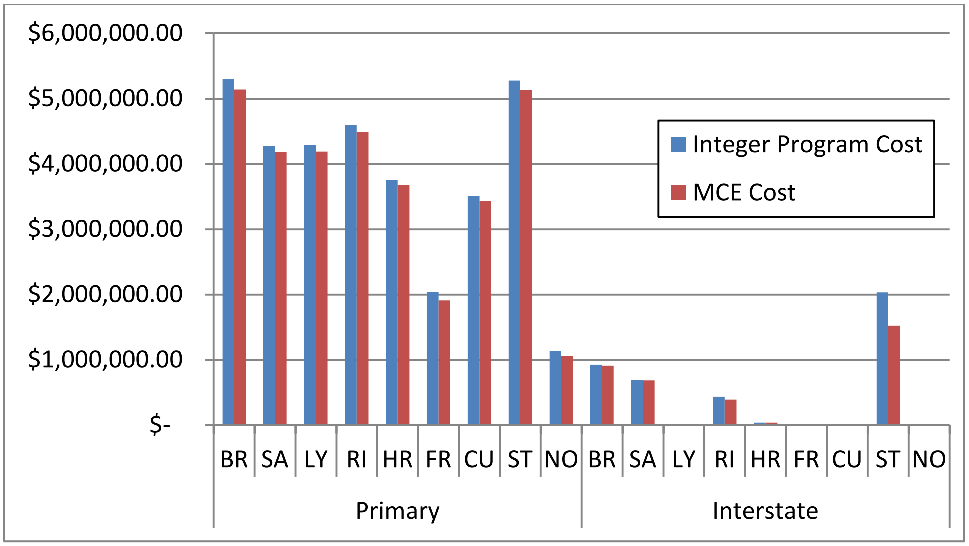


Figure 30. Cost for Integer Program and MCE Computations by District and Pavement Classification

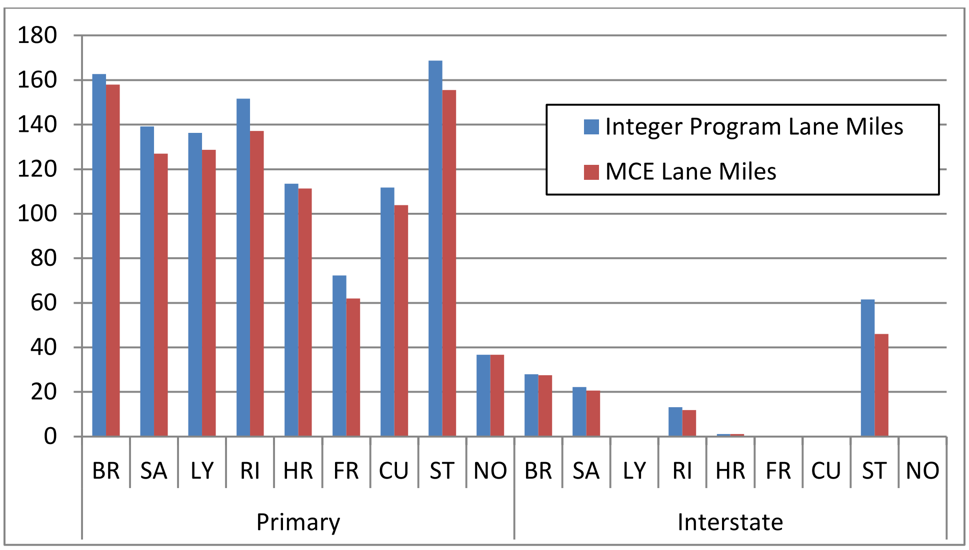


Figure 31. Lane Miles for Integer Program and MCE Computations by District and Pavement Classification

The total cost of PM treatments and the respective lane mile recommendations developed using the MCE method were marginally lower than the results obtained from the true optimization. In many cases, instead of selecting one section with a high cost-benefit ratio, the optimization method selects multiple sections, each having a lower cost-benefit ratio. The sum of the cost benefit ratios of the multiple-section-selection exceeds the cost benefit ratio of the single section. The true optimization method therefore has the ability to exhaust more of the budget, by selecting sections that may have a lower priority because of their cost-benefit ratio.

Although the integer program methodology provides an optimal selection of pavement sections for preventive maintenance, it is difficult to implement an optimization procedure into an automated tool using the available Microsoft Excel Solver Add-in. This software has a limitation of 200 decision variables. If there are more than 200 pavement sections that are eligible for preventive maintenance in a district, the tool would not work. The results of the verification, however, show that the MCE method, which is less complex than true optimization, provides comparable recommendations for preventive maintenance.

District personnel can use the tool to identify feasible preventive maintenance treatments for each section. The treatment feasibility capability of the tool is particularly important, because it would provide consistent recommendations across the state for inputs such as pavement age, traffic level, and distress type and severity. As preventive maintenance treatment performance is monitored over time, the models can be updated. The final pavement section selections made by the tool can then be improved by updating the expected treatment performance specific to each district. The treatment selection tool outlined in this chapter is a useful decision support tool that can be immediately implemented in the Virginia maintenance districts.

CHAPTER VI - SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

Preventive maintenance retards future deterioration of the pavement by sealing the pavement's surface and preventing the infiltration of water into the pavement structure. Preventive maintenance keeps good pavements in good condition, and since these treatments are relatively cheap when compared to traditional rehabilitation methods, they can lower the total cost of maintenance while maintaining or even improving pavement condition.

When agencies are able to use pavement management systems to determine the effect of different maintenance strategies, they are more likely to implement a preventive maintenance policy which has the ability to improve network condition while being constrained by budgetary concerns. Pavement management systems allow highway agencies the ability to store pavement data in one central database which promotes condition monitoring over time for the development of expected performance models for future condition prediction, and also illustrates the effect of maintenance strategies and budgets on network condition.

The Virginia Department of Transportation uses its pavement management system to perform network analysis to determine maintenance targets for each district, including maintenance type, and lane miles and budget for each maintenance type. The districts then use these recommendations to select pavements that will receive maintenance and the types of treatments that will be applied. Each district has a different approach to preventive maintenance. Pavement condition triggers and treatments applied vary between districts. There was a need for more consistent preventive maintenance practices across the state.

Preventive maintenance treatments currently being used within Virginia include chip seal, slurry seal, microsurfacing, and thin hot mix asphalt overlays. Historical pavement condition data was obtained from the VDOT PMS for these treatments and treatment performance models were developed. An outlier analysis was performed to remove anomalies within the data, such as CCI values that were too low or too high.

A district level treatment selection tool was developed in to assist the district level decision making process. First, treatment feasibility was identified for each pavement section, and the most cost effective feasible treatment was assigned to each pavement section. Next, a prioritized list of pavement sections was generated, maximizing the cost-effectiveness of the selected treatments subject to budgetary and lane mile constraints set by the central office.

The treatment selection tool was then run for each pavement classification (interstate and primary) in each district. The results of this analysis suggest that the estimated cost of preventive maintenance used to develop central office recommendations is significantly lower than the cost of preventive maintenance treatments used in this thesis. Although the recommended budget for each district was very close to the targets set by the central office, the recommended lane miles for each district were lower than the targets set by the central office. This was because the cost of preventive maintenance calculated within the PMS uses a weighted average of current activities, which are mostly crack sealing and patching. The treatment costs for slurry seal, microsurfacing, and THMACO were significantly greater than the preventive maintenance costs estimated by the central office.

FINDINGS

It was found that the Virginia Department of Transportation has implemented a maintenance category selection methodology involving decision trees and decision matrices. Though helpful, this methodology provides only general maintenance categories such as DN, PM, CM, RM, and RC, but does not suggest specific treatments to be applied to pavement sections.

Of the three districts visited, it was found that each district used different criteria for which pavements received preventive maintenance, and which preventive maintenance treatments were applied.

When analyzing the treatment performance data, it was found that there were several instances where section performance increased over time. This was attributed to intermediate treatments being applied, such as crack seals, which can improve section condition. If these treatments are not recorded, the treatment performance trend can artificially be made to increase over time, implying that pavements get better over time without any new treatments applied.

It was also found that there were several sections which did not have performance data available for the early life of the pavement section, but had data available for later pavement ages. In these instances, the condition data often had a relatively high value at a relatively late date in the pavement's life. This was thought to be due to to preventive maintenance treatments being applied without having the last treatment year updated.

Pre-treatment condition was unavailable for many sections. In many cases, section location changed with preventive maintenance treatment applications. The begin mile point and end mile point data for sections before preventive maintenance and after preventive maintenance were often changed.

In the development of the treatment performance models, it was found that THMACO and chip seal had the highest expected performance of the four treatments. Slurry seal and microsurfacing treatments have the potential to provide benefit to pavement performance; however, if these treatments are applied in sub-optimal conditions, their benefit is negligible.

In the development and execution of the district level selection tool, it was found that the treatments recommended for application were mainly THMACO and chip seal. It is believed that the high expected performance of THMACO and chip seal as well as the low expected performance of slurry seal and microsurfacing as developed in Chapter V created a bias in favor of selection of THMACO and chip seal.

CONCLUSIONS

This thesis presents recommendations for implementation of a preventive maintenance policy based on consistent guidelines that can be used in Virginia maintenance districts. Data from the VDOT PMS was used to develop treatment performance curves for each of the four treatments (Microsurfacing, Slurry Seal, Chip Seal, and THMACO). The recommended preventive maintenance policy was used to develop a district level decision making tool for use in the maintenance districts in Virginia. This tool determines the near-optimal treatment selection for each pavement maintenance section and provides a prioritized list of pavements to receive these treatments. Integration of the recommended preventive maintenance policy which supports the PMS is expected to yield a significant benefit.

RECOMMENDATIONS

Implementation Recommendations

The implementation recommendations are to:

- Avoid a “worst first” approach. If possible, preventive maintenance should be used in tandem with major rehabilitation to establish a balance: fix the roads that are in dire need of repair, while preventing good roads from deteriorating to that point.
- Use the results of the VDOT PMS decision matrix analysis as a starting point for treatment selection. This analysis provides maintenance category recommendations so that network condition can be improved over time.
- Use a consistent approach for determining treatment feasibility within each district.
- Obtain cost data specific to each district, so that the most accurate cost and cost-effectiveness estimations can be computed.
- Implement this district level treatment selection tool for use in the maintenance districts in Virginia.

Recommendations to Improve Models

Recommendations that can improve the models used are to:

- Perform a review of existing pavement data in the PMS so that pavement age and condition data reflect the actual conditions of the pavement.
- Continue to monitor pavement performance over time and update the PMS so that deterioration models can be updated and improved.
- Ensure that all pavement treatments are recorded so that increases in pavement condition correspond to a treatment being applied to that pavement.

Recommendations for Future Research

Recommendations for future work based on this thesis are to:

- Implement an optimization procedure independent of the Microsoft Excel Solver Add-in using Visual Basic to avoid limits on the number of decision variables within the tool.
- Incorporate continuity constraints in project level selection for construction considerations.

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APPENDIX

APPENDIX A: VDOT PM DECISION MATRICES

Table A. 1. Notations and Terminology [30]

Notation	*Terminology*
Distress Density	
N	None
R	Rare
O	Occasional
F	Frequent
P0	No Patching
P1	< 10% Pavement Area Patched
P2	> 10% Pavement Area Patched
Distress Severity Levels	
NS	Not Severe
S	Severe
VS	Very Severe
Maintenance Activity Category	
DN	Do Nothing
PM	Preventive Maintenance
CM	Corrective Maintenance
RM	Restorative Maintenance
RC	Rehabilitation / Reconstruction

Table A. 2. Decision Matrix for Alligator Cracks [30]

Alligator Cracking			
Frequency	**R**	**O**	**F**
Severity			
NS	DN	DN	**PM**
S	DN	**PM**	CM
VS	CM	CM	RM

Table A. 3. Decision Matrix for Transverse Cracks [30]

Transverse Cracks/Per Mile				
Frequency	**0 – 50**	**51 – 74**	**75 – 199**	**≥ 200**
Severity				
NS	DN	DN	DN	**PM**
S	DN	DN	**PM**	CM
VS	CM	RM	RC	RC
Note: For Transverse Cracking, VS applies to composite pavements only				

Table A. 4. Decision Matrix for the Combination of Alligator and Transverse Cracking [30]

			Alligator Cracking								
Frequency			**R**			**O**			**F**		
		Severity	**NS**	**S**	**VS**	**NS**	**S**	**VS**	**NS**	**S**	**VS**
Transverse Cracking/Mile	**0 – 50**	NS	DN	DN	**PM**	DN	**PM**	CM	**PM**	CM	RM
		S	DN	DN	CM	DN	**PM**	CM	**PM**	CM	RM
		VS	CM	CM	CM	CM	CM	CM	CM	RM	RM
	51 - 74	NS	DN	DN	**PM**	DN	**PM**	CM	**PM**	CM	RM
		S	DN	DN	CM	DN	**PM**	CM	**PM**	CM	RM
		VS	RM	RM	RM	RM	RM	RM	RM	RM	RM
	75 - 199	NS	DN	DN	CM	DN	**PM**	CM	**PM**	CM	RM
		S	CM	CM	CM	CM	CM	CM	CM	CM	RM
		VS	RC	RC	RC	RC	RC	RC	RC	RC	RC
	≥200	NS	**PM**	**PM**	CM	**PM**	**PM**	CM	**PM**	CM	RM
		S	CM	CM	CM	CM	CM	CM	CM	CM	RM
		VS	RC	RC	RC	RC	RC	RC	RC	RC	RC
Note: For Transverse Cracking, VS applies to composite pavement only.											

Table A. 5. Decision Matrix for the Combination of Alligator Cracking and Rutting [30]

			Alligator Cracking								
Frequency			**R**			**O**			**F**		
		Severity	**NS**	**S**	**VS**	**NS**	**S**	**VS**	**NS**	**S**	**VS**
Rutting	**< 10%**	**N**	DN	DN	CM	DN	**PM**	CM	**PM**	CM	RM
		< .5"	DN	DN	CM	DN	**PM**	CM	**PM**	CM	RM
		> .5"	CM	CM	CM	CM	CM	RM	CM	RM	RM
	>10%	**N**	DN	DN	CM	DN	**PM**	CM	**PM**	CM	RM
		< .5"	CM	CM	CM	CM	CM	CM	CM	RM	RM
		> .5"	RM	RM	RM	RM	RM	RM	RM	RC	RC

Table A. 6. Decision Matrix for the Combination of Transverse Cracking and Rutting [30]

			Transverse Cracking/Mile											
Frequency			**0 – 50**			**51 – 74**			**75 - 199**			**≥200**		
		Severity	**NS**	**S**	**VS**	**NS**	**S**	**VS**	**NS**	**S**	**VS**	**NS**	**S**	**VS**
Rutting	**< 10%**	**N**	DN	DN	CM	DN	DN	RM	DN	**PM**	RC	**PM**	CM	RC
		< 0.5"	DN	DN	CM	DN	DN	RM	DN	**PM**	RC	**PM**	CM	RC
		> 0.5"	CM	CM	CM	CM	CM	RM	CM	CM	RC	CM	CM	RC
	>10%	**N**	DN	DN	CM	DN	DN	RM	DN	**PM**	RC	**PM**	CM	RC
		< 0.5"	CM	CM	CM	CM	CM	RM	CM	CM	RC	CM	RM	RC
		> 0.5"	RM	RM	RM	RM	RM	RM	RM	RM	RC	RM	RM	RC
Note: For Transverse Cracking, VS applies to composite pavement only.														

Table A. 7. Decision Matrix for the Combination of Transverse Cracking and Patching [30]

		Transverse Cracking/Mile											
Frequency		**0 – 50**			**51 - 74**			**75 - 199**			**≥200**		
Severity		**NS**	**S**	**VS**	**NS**	**S**	**VS**	**NS**	**S**	**VS**	**NS**	**S**	**VS**
Patch	**N**	DN	DN	CM	DN	DN	RM	DN	**PM**	RC	**PM**	CM	RC
	< 10%	DN	DN	CM	DN	DN	RM	DN	**PM**	RC	**PM**	CM	RC
	> 10%	CM	CM	RM	CM	CM	RM	CM	RM	RC	CM	RM	RC
Note: For Transverse Cracking, VS applies to composite pavement only.													

Table A. 8. Decision Matrix for the Combination of Alligator Cracking and Patching [30]

		Alligator Cracking								
Frequency		R			O			F		
	Severity	NS	S	VS	NS	S	VS	NS	S	VS
Patch	N	DN	DN	CM	DN	**PM**	CM	**PM**	CM	RM
	< 10%	DN	DN	CM	DN	**PM**	CM	**PM**	CM	RM
	> 10%	CM	CM	CM	CM	RM	RM	CM	RM	RC

Table A. 9. Decision Matrix for the Combination of Rare Alligator Cracking, Transverse Cracking, and Patching [30]

Alligator Cracking Frequency			Rare								
Alligator Cracking Severity			NS (DN)			S (DN)			VS (CM)		
Patching Frequency			P0	P1	P2	P0	P1	P2	P0	P1	P2
Transverse Cracks per mile	0-50	NS	DN	DN	CM	DN	DN	CM	CM	CM	CM
		S	DN	DN	CM	DN	DN	CM	CM	CM	CM
		VS	CM	CM	RM	CM	CM	RM	CM	CM	RM
	51-74	NS	DN	DN	CM	DN	DN	CM	CM	CM	CM
		S	DN	DN	CM	DN	**PM**	CM	CM	CM	CM
		VS	RM	RM	RM	RM	RM	RM	RM	RM	RM
	75-199	NS	DN	DN	CM	DN	DN	CM	CM	CM	CM
		S	**PM**	**PM**	**RM**	**PM**	**PM**	RM	CM	CM	RM
		VS	RC	RC	RC	RC	RC	RC	RC	RC	RC
	>=200	NS	**PM**	**PM**	CM	PM	PM	CM	CM	CM	CM
		S	CM	CM	RM	CM	CM	RM	CM	CM	RM
		VS	RC	RC	RC	RC	RC	RC	RC	RC	RC

Table A. 10. Decision Matrix for the Combination of Occasional Alligator Cracking, Transverse Cracking, and Patching [30]

Alligator Cracking Frequency			**Occasional**								
Alligator Cracking Severity			**NS (DN)**			**S (PM)**			**VS (CM)**		
Patching Frequency			**P0**	**P1**	**P2**	**P0**	**P1**	**P2**	**P0**	**P1**	**P2**
Transverse Cracks per mile	**0-50**	**NS**	DN	DN	CM	**PM**	**PM**	RM	CM	CM	RM
		S	DN	DN	CM	**PM**	**PM**	RM	CM	CM	RM
		VS	CM	CM	RM	CM	CM	RM	CM	CM	RM
	51-74	**NS**	DN	**PM**	CM	**PM**	**PM**	RM	CM	CM	RM
		S	DN	**PM**	CM	**PM**	**PM**	RM	CM	CM	RM
		VS	RM	RM	RM	RM	RM	RM	RM	RM	RM
	75-199	**NS**	DN	**PM**	CM	**PM**	**PM**	RM	CM	CM	RM
		S	**PM**	**PM**	**RM**	**PM**	**PM**	RM	CM	CM	RM
		VS	RC	RC	RC	RC	RC	RC	RC	RC	RC
	>=200	**NS**	**PM**	**PM**	CM	**PM**	**PM**	RM	CM	CM	RM
		S	CM	CM	RM	CM	CM	RM	CM	CM	RM
		VS	RC	RC	RC	RC	RC	RC	RC	RC	RC

Table A. 11. Decision Matrix for the Combination of Frequent Alligator Cracking, Transverse Cracking, and Patching [30]

Alligator Cracking Frequency			**Frequent**								
Alligator Cracking Severity			**NS (PM)**			**S (CM)**			**VS (RM)**		
Patching Frequency			**P0**	**P1**	**P2**	**P0**	**P1**	**P2**	**P0**	**P1**	**P2**
Transverse Cracks per mile	**0-50**	**NS**	**PM**	**PM**	CM	CM	CM	RM	RM	RM	RC
		S	**PM**	**PM**	CM	CM	CM	RM	RM	RM	RC
		VS	CM	CM	RM	RM	RM	RM	RM	RM	RC
	51-74	**NS**	**PM**	**PM**	CM	CM	CM	RM	RM	RM	RC
		S	**PM**	**PM**	CM	CM	CM	RM	RM	RM	RC
		VS	RM	RM	RM	RM	RM	RM	RM	RM	RC
	75-199	**NS**	**PM**	**PM**	CM	CM	CM	RM	RM	RM	RC
		S	**PM**	**PM**	RM	CM	CM	RM	RM	RM	RC
		VS	RC	RC	RC	RC	RC	RC	RC	RC	RC
	>=200	**NS**	**PM**	**PM**	CM	CM	CM	RM	RM	RM	RC
		S	CM	CM	RM	CM	RM	RM	RM	RM	RC
		VS	RC	RC	RC	RC	RC	RC	RC	RC	RC

Table A. 12. Decision Matrix for the Combination of Rare Alligator Cracking, Rutting, and Patching [30]

Alligator Cracking Frequency			**Rare**								
Alligator Cracking Severity			**NS (DN)**			**S (DN)**			**VS (CM)**		
Patching Frequency			**P0**	**P1**	**P2**	**P0**	**P1**	**P2**	**P0**	**P1**	**P2**
Rutting	**None**	**N/A**	DN	DN	CM	DN	DN	CM	CM	CM	CM
	< 10%	**<0.5"**	DN	DN	CM	DN	**PM**	CM	CM	CM	CM
		>0.5"	CM	CM	RM	CM	CM	RM	CM	CM	RM
	> 10%	**<0.5"**	CM	CM	RM	CM	CM	RM	CM	CM	RM
		>0.5"	RM	RM	RC	RM	RM	RC	RM	RM	RC

Table A. 13. Decision Matrix for the Combination of Occasional Alligator Cracking, Rutting, and Patching [30]

Alligator Cracking Frequency			**Occasional**								
Alligator Cracking Severity			**NS (DN)**			**S (PM)**			**VS (CM)**		
Patching Frequency			**P0**	**P1**	**P2**	**P0**	**P1**	**P2**	**P0**	**P1**	**P2**
Rutting	**None**	**N/A**	DN	DN	CM	**PM**	**PM**	RM	CM	CM	RM
	< 10%	**<0.5"**	DN	**PM**	CM	PM	CM	RM	CM	CM	RM
		>0.5"	CM	CM	RM	CM	CM	RM	RM	RM	RM
	> 10%	**<0.5"**	CM	CM	RM	CM	CM	RM	CM	CM	RM
		>0.5"	RM	RM	RC	RM	RM	RC	RM	RM	RC

Table A. 14. Decision Matrix for the Combination of Frequent Alligator Cracking, Rutting, and Patching [30]

Alligator Cracking Frequency			**Frequent**								
Alligator Cracking Severity			**NS (PM)**			**S (CM)**			**VS (RM)**		
Patching Frequency			**P0**	**P1**	**P2**	**P0**	**P1**	**P2**	**P0**	**P1**	**P2**
Rutting	**None**	**N/A**	**PM**	**PM**	CM	CM	CM	RM	RM	RM	RC
	< 10%	**<0.5"**	**PM**	**PM**	CM	CM	CM	RM	RM	RM	RC
		>0.5"	CM	CM	RM	RM	RM	RM	RM	RM	RC
	> 10%	**<0.5"**	CM	CM	RM	RM	RM	RM	RM	RM	RC
		>0.5"	RM	RM	RC	RC	RC	RC	RC	RC	RC

Table A. 15. Decision Matrix for the Combination of Rutting, Transverse Cracking, and Patching [30]

Rutting Frequency			None			<10%						>10%					
Rutting Severity			**N/A (DN)**			**<0.5" (DN)**			**>0.5" (CM)**			**<0.5" (CM)**			**>0.5" (RM)**		
Patching Frequency			**P0**	**P1**	**P2**	**P0**	**P1**	**P2**	**P0**	**P1**	**P2**	**P0**	**P1**	**P2**	**P0**	**P1**	**P2**
Transverse Cracks per mile		**NS**	DN	DN	CM	DN	DN	CM	CM	CM	RM	CM	CM	RM	RM	RM	RC
		S	DN	DN	CM	DN	DN	CM	CM	CM	RM	CM	CM	RM	RM	RM	RC
	0-50	**VS**	CM	CM	RM	CM	CM	RM	CM	CM	RM	CM	CM	RM	RM	RM	RC
		NS	DN	DN	CM	DN	DN	CM	CM	CM	RM	CM	CM	RM	RM	RM	RC
		S	DN	DN	CM	DN	DN	CM	CM	CM	RM	CM	CM	RM	RM	RM	RC
	51-74	**VS**	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RC
		NS	DN	DN	CM	DN	DN	CM	CM	CM	RM	CM	CM	RM	RM	RM	RC
		S	**PM**	**PM**	RM	**PM**	**PM**	RM	CM	CM	RM	CM	CM	RM	RM	RM	RC
	75-199	**VS**	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
		NS	**PM**	**PM**	CM	**PM**	**PM**	CM	CM	CM	RM	CM	CM	RM	RM	RM	RC
		S	CM	CM	RM	CM	CM	RM	CM	CM	RM	RM	RM	RM	RM	RM	RC
	>=200	**VS**	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC

Table A. 16. Decision Matrix for the Combination of Rare Alligator Cracking, Rutting, Transverse Cracking, and Patching [30]

Alligator Crack Frequency				**Rare**																	
Alligator Crack Severity				**NS (DN)**						**Severe (DN)**						**Very Severe (CM)**					
Rutting Freq.				**N**		**<10%**		**>10%**		**N**		**<10%**		**>10%**		**N**		**<10%**		**>10%**	
Rutting Severity				**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**
Transverse cracks per mile	**0-50**	**NS (DN)**	P0	DN	DN	DN	CM	CM	RM	DN	DN	DN	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P1	DN	DN	DN	CM	CM	RM	DN	DN	**PM**	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P2	CM	CM	CM	RM	RM	RC	CM	CM	CM	RM	RM	RC	CM	CM	CM	RM	RM	RC
		S (DN)	P0	DN	DN	DN	CM	CM	RM	DN	DN	DN	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P1	DN	DN	DN	CM	CM	RM	DN	DN	**PM**	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P2	CM	CM	CM	RM	RM	RC	CM	CM	CM	RM	RM	RC	CM	CM	CM	RM	RM	RC
		VS (CM)	P0	CM	CM	CM	CM	CM	RM	CM	CM	CM	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P1	CM	CM	CM	CM	CM	RM	CM	CM	CM	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P2	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
	51-74	**NS (DN)**	P0	DN	DN	DN	CM	CM	RM	DN	DN	DN	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P1	DN	DN	DN	CM	CM	RM	DN	DN	PM	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P2	CM	CM	CM	RM	RM	RC	CM	CM	CM	RM	RM	RC	CM	CM	CM	RM	RM	RC
		S (DN)	P0	DN	DN	DN	CM	CM	RM	DN	DN	DN	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P1	DN	DN	DN	CM	CM	RM	PM	PM	PM	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P2	CM	CM	CM	RM	RM	RC	CM	CM	CM	RM	RM	RC	CM	CM	CM	RM	RM	RC
		VS (RM)	P0	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM
			P1	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM
			P2	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
	75-199	**NS (DN)**	P0	DN	DN	DN	CM	CM	RM	DN	DN	DN	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P1	DN	DN	DN	CM	CM	RM	DN	DN	PM	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P2	CM	CM	CM	RM	RM	RC	CM	CM	CM	RM	RM	RC	CM	CM	CM	RM	RM	RC
		S (PM)	P0	**PM**	**PM**	**PM**	CM	CM	RM	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P1	**PM**	**PM**	**PM**	CM	CM	RM	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P2	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
		VS (RC)	P0	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
			P1	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
			P2	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
	>=200	**NS (PM)**	P0	**PM**	**PM**	**PM**	CM	CM	RM	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P1	**PM**	**PM**	**PM**	CM	CM	RM	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	CM	CM	RM
			P2	CM	CM	CM	RM	RM	RC	CM	CM	CM	RM	RM	RC	CM	CM	CM	RM	RM	RC
		S (CM)	P0	CM	CM	CM	CM	RM	RM	CM	CM	CM	CM	RM	RM	CM	CM	CM	CM	RM	RM
			P1	CM	CM	CM	CM	RM	RM	CM	CM	CM	CM	RM	RM	CM	CM	CM	CM	RM	RM
			P2	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
		VS (RC)	P0	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
			P1	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
			P2	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC

Table A. 17. Decision Matrix for the Combination of Occasional Alligator Cracking, Rutting, Transverse Cracking, and Patching [30]

Alligator Crack Frequency				**Occasional**																	
Alligator Crack Severity				**Not Severe (DN)**						**Severe (PM)**						**Very Severe (CM)**					
Rutting Frequency				**N**		**<10%**		**>10%**		**N**		**<10%**		**>10%**		**N**		**<10%**		**>10%**	
Rutting Severity				**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**	**<0.5"**	**>0.5"**
Transverse cracks per mile	**0-50**	**NS (DN)**	P0	DN	DN	DN	CM	CM	RM	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P1	DN	DN	**PM**	CM	CM	RM	**PM**	**PM**	CM	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P2	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
		S (DN)	P0	DN	DN	DN	CM	CM	RM	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P1	DN	DN	**PM**	CM	CM	RM	**PM**	**PM**	CM	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P2	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
		VS (CM)	P0	CM	CM	CM	CM	CM	RM	CM	CM	CM	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P1	CM	CM	CM	CM	CM	RM	CM	CM	CM	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P2	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
	51-74	**NS (DN)**	P0	DN	DN	DN	CM	CM	RM	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P1	**PM**	**PM**	**PM**	CM	CM	RM	**PM**	**PM**	CM	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P2	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
		S (DN)	P0	DN	DN	DN	CM	CM	RM	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P1	**PM**	**PM**	**PM**	CM	CM	RM	**PM**	**PM**	CM	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P2	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
		VS (RM)	P0	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM
			P1	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM
			P2	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
	75-199	**NS (DN)**	P0	DN	DN	DN	CM	CM	RM	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P1	**PM**	**PM**	**PM**	CM	CM	RM	**PM**	**PM**	CM	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P2	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
		S (PM)	P0	**PM**	**PM**	**PM**	CM	CM	RM	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P1	**PM**	**PM**	**PM**	CM	CM	RM	**PM**	**PM**	CM	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P2	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
		VS (RC)	P0	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
			P1	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
			P2	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
	>=200	**NS (PM)**	P0	**PM**	**PM**	**PM**	CM	CM	RM	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P1	**PM**	**PM**	**PM**	CM	CM	RM	**PM**	**PM**	CM	CM	CM	RM	CM	CM	CM	RM	CM	RM
			P2	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
		S (CM)	P0	CM	CM	CM	CM	RM	RM	CM	CM	CM	CM	RM	RM	CM	CM	CM	RM	RM	RM
			P1	CM	CM	CM	CM	RM	RM	CM	CM	CM	CM	RM	RM	CM	CM	CM	RM	RM	RM
			P2	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
		VS (RC)	P0	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
			P1	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
			P2	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC

Table A. 18. Decision Matrix for the Combination of Frequent Alligator Cracking, Rutting, Transverse Cracking, and Patching [30]

Alligator Crack Frequency				Frequent																	
Alligator Crack Severity				Not Severe (PM)						Severe (CM)						Very Severe (RM)					
Rutting Frequency				N		<10%		>10%		N		<10%		>10%		N		<10%		>10%	
Rutting Severity				<0.5"	>0.5"	<0.5"	>0.5"	<0.5"	>0.5"	<0.5"	>0.5"	<0.5"	>0.5"	<0.5"	>0.5"	<0.5"	>0.5"	<0.5"	>0.5"	<0.5"	>0.5"
Transverse cracks per mile	0-50	NS (DN)	P0	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P1	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P2	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RC	RC	RC	RC	RC	RC
		S (DN)	P0	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P1	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P2	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RC	RC	RC	RC	RC	RC
		VS (CM)	P0	CM	CM	CM	CM	CM	RM	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P1	CM	CM	CM	CM	CM	RM	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P2	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RC	RC	RC	RC	RC	RC
	51-74	NS (DN)	P0	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P1	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P2	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RC	RC	RC	RC	RC	RC
		S (DN)	P0	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P1	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P2	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RC	RC	RC	RC	RC	RC
		VS (RM)	P0	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P1	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P2	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RC	RC	RC	RC	RC	RC
	75-199	NS (DN)	P0	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P1	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P2	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RC	RC	RC	RC	RC	RC
		S (PM)	P0	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P1	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P2	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RC	RC	RC	RC	RC	RC
		VS (RC)	P0	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
			P1	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
			P2	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
	>=200	NS (PM)	P0	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P1	**PM**	**PM**	**PM**	CM	CM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P2	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RC	RC	RC	RC	RC	RC
		S (CM)	P0	CM	CM	CM	CM	RM	RM	CM	CM	CM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P1	CM	CM	CM	CM	RM	RM	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC
			P2	RM	RM	RM	RM	RM	RC	RM	RM	RM	RM	RM	RC	RC	RC	RC	RC	RC	RC
		VS (RC)	P0	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
			P1	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
			P2	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC

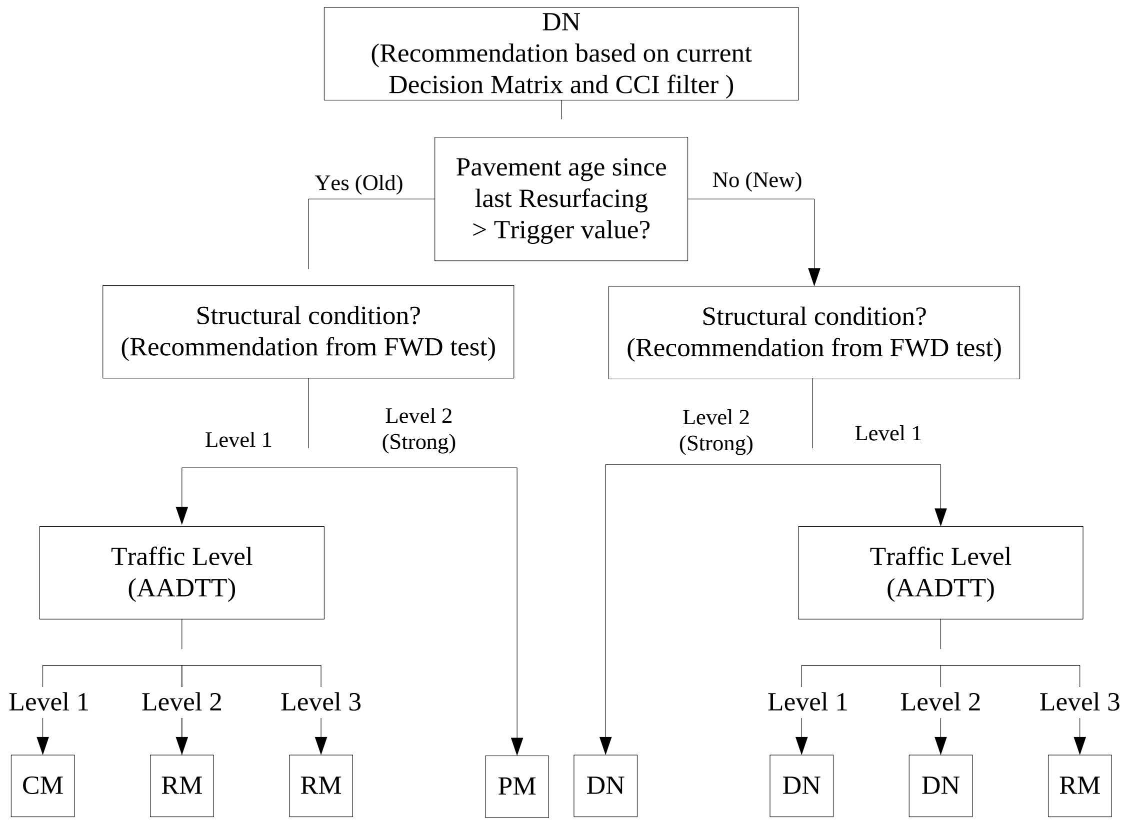

Figure A. 1. Decision Tree for IS BIT with DN as Initial Treatment [30]

Table A. 19. Trigger values for DN IS BIT Decision Tree [30]

<table>
<tr><td></td><td colspan="4">Trigger Values</td></tr>
<tr><td rowspan="2">Age
(years)</td><td colspan="2">New</td><td colspan="2">Old</td></tr>
<tr><td colspan="2">≤ 6</td><td colspan="2">> 6</td></tr>
<tr><td rowspan="2">FWD
(BIT: SN & M_R
BOC/BOJ: AREA & k)</td><td colspan="2">Level 2 (Strong)</td><td colspan="2">Level 1</td></tr>
<tr><td colspan="2">$SN \geq 6$ & $M_R \geq 10,000$ psi
or
$AREA \geq 32$ in. & $k \geq 175$ pci</td><td colspan="2">Otherwise</td></tr>
<tr><td rowspan="2">Traffic
(AADTT)</td><td>Level 1</td><td colspan="2">Level 2</td><td>Level 3</td></tr>
<tr><td>< 1500</td><td colspan="2">[1500, 5000]</td><td>> 5000</td></tr>
</table>

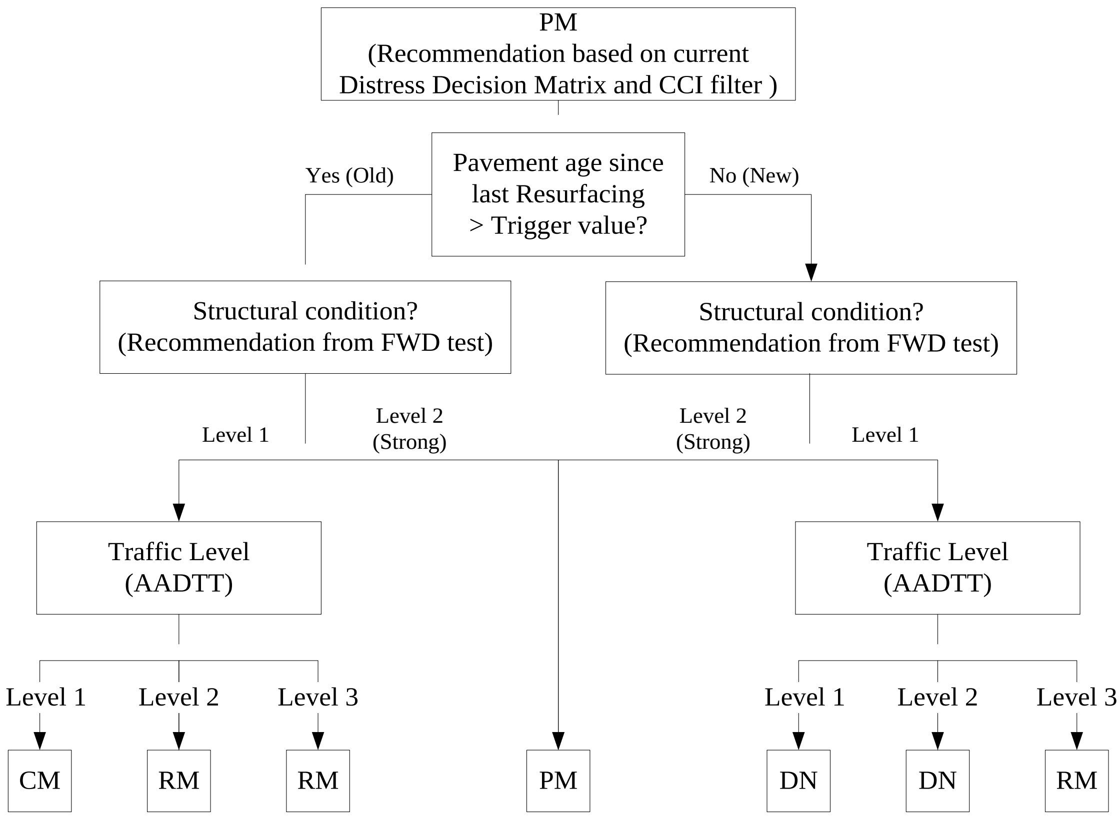

Figure A. 2. Decision Tree for IS BIT with PM as Initial Treatment [30]

Table A. 20. Trigger values for PM IS BIT Decision Tree [30]

	Trigger Values		
Age (years)	**New**		**Old**
	≤6		***> 6***
FWD (BIT: SN & M_R BOC/BOJ: AREA & k)	**Level 2 (Strong)**		**Level 1**
	SN ≥ 6 & M_R ≥ 10,000 psi or AREA ≥ 32 in. & k ≥ 175 pci		***Otherwise***
Traffic (AADTT)	**Level 1**	**Level 2**	**Level 3**
	< 1500	***[1500, 5000]***	***> 5000***

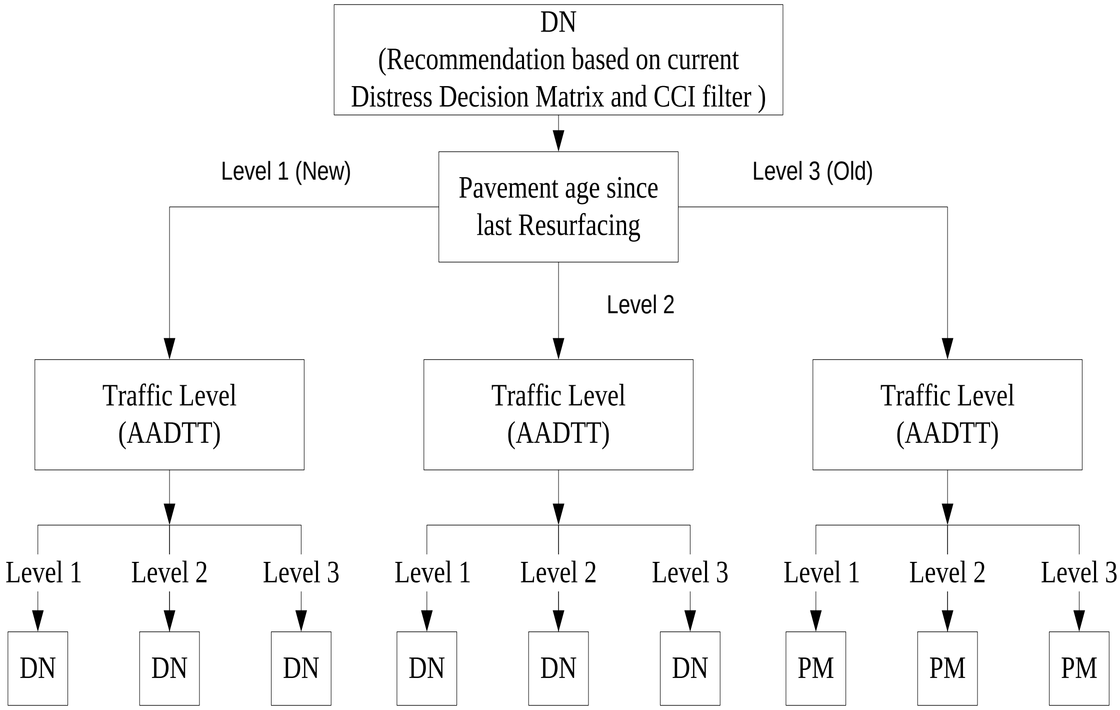

Figure A. 3. Decision Tree for PR BIT with DN as Initial Treatment [30]

Table A. 21. Trigger values for DN PR BIT Decision Tree [30]

	Trigger Values		
Age (years)	**Level 1**	**Level 2**	**Level 3**
	< *5*	**[*5, 10*]**	**> *10***
Traffic (AADTT)	**Level 1**	**Level 2**	**Level 3**
	< *50*	**[*50, 300*]**	**> *300***

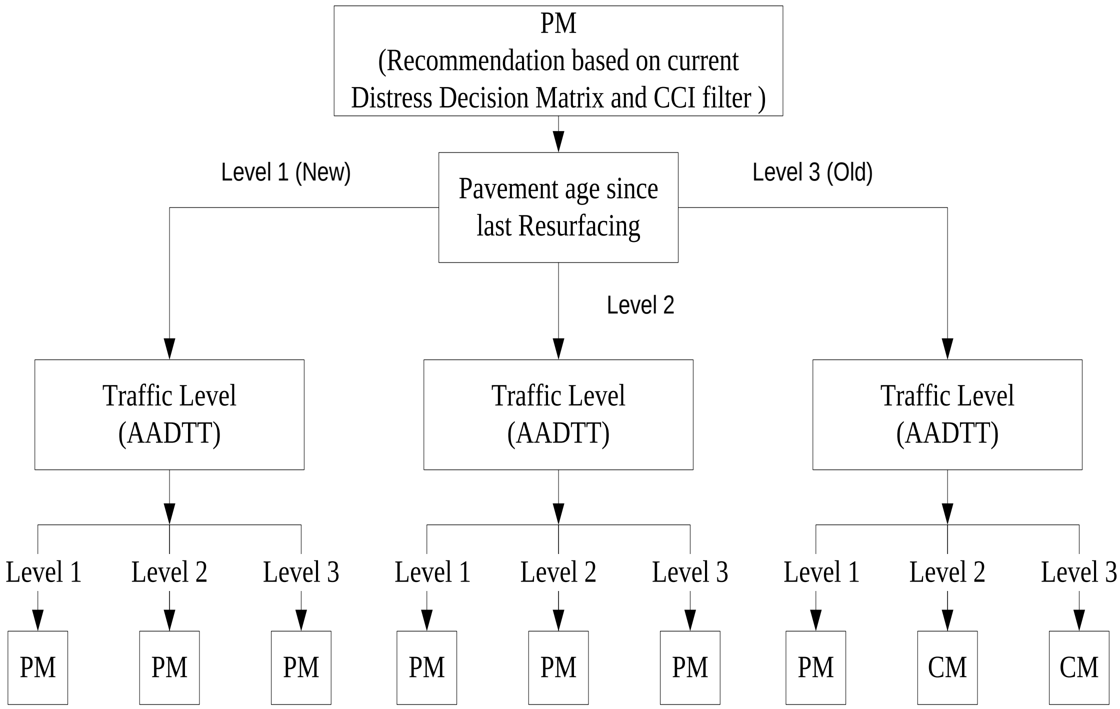

Figure A. 4. Decision Tree for PR BIT with PM as Initial Treatment [30]

Table A. 22. Trigger values for PM PR BIT Decision Tree [30]

	Trigger Values		
Age (years)	**Level 1**	**Level 2**	**Level 3**
	< *5*	**[*5, 10*]**	**> *10***
Traffic (AADTT)	**Level 1**	**Level 2**	**Level 3**
	< *50*	**[*50, 300*]**	**> *300***