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Best Practices and Performance Assessment for Preventive Maintenance Treatments for Virginia Pavements

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FINAL REPORT

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ABSTRACT

Preventive maintenance has the potential to improve network condition by retarding future pavement deterioration. This report outlines guidelines for implementing a preventive maintenance policy for bituminous pavements.

Preventive maintenance treatments currently being used in Virginia include chip seal, slurry seal, microsurfacing, and thin hot mix asphalt overlays. Historical pavement condition data were obtained from the Virginia Department of Transportation's Pavement Management System for these treatments, and treatment performance models were developed. A district-level treatment selection tool was developed to facilitate 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. As a pilot implementation, the treatment selection tool was then run for each pavement classification in each district. The results of this pilot suggest that this selection tool has the potential to be a practical decision support tool.

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INTRODUCTION

The majority of the highways in Virginia were built as a response to the increased use of automobiles in the rapidly growing urban areas, especially from the 1960s to the 1970s during the expansion of the interstate system. By the 1980s, most of these roads had been heavily used and had started showing signs of distress, and the state was forced to shift attention to their rehabilitation. A similar trend has been observed at the national level.

This shift caught agencies "allocating the limited available funds on a worst-first basis, reducing the number of miles they could treat each year which resulted in a decrease in the overall condition of the pavement network" (Peshkin et al., 2003). Since then, pavement managers have learned that it is actually more cost-effective not to allow pavements to freely deteriorate to the point of rehabilitation but instead to prolong the good condition through a series of intermediate, smaller maintenance actions known as preventive maintenance.

The problem with the preventive maintenance approach, however, is *which* treatments to use and *when* to use them, for any particular pavement situation. The literature indicates that properly designed and implemented preventive maintenance strategies save money in the long term and enhance the sustainability of our road infrastructure. Engineers now know that timely application of preventive maintenance practices will in fact produce a more "cost-effective means of obtaining the desired life and performance of a pavement" (Peshkin et al., 2003).

Unfortunately, there are still questions pertaining to the functional performance of the various preventive maintenance treatments (e.g., friction) over time and their effect on extending pavement service life. Traffic demand, climatic conditions, and treatment costs are among the many important factors that may make some alternatives more effective than others in different situations. Some of these questions can be answered by taking advantage of the agency's Pavement Management System (PMS).

In Virginia, the Virginia Department of Transportation (VDOT) Central Office Maintenance Division provides recommendations to each district regarding treatment categories, budget, and total lane-miles to be maintained within each road category (interstate, primary, and secondary). Within each district, the pavement managers select which pavements receive maintenance as well as their specific treatments. Most districts have different criteria that can qualify a pavement for consideration for preventive maintenance, and treatment selection is based on engineering experience. Over time, each district has developed its own preventive maintenance policy, and preventive maintenance treatment selection varies across the state.

Furthermore, budget reductions have affected the amount of maintenance and rehabilitation work that can be done every year. In 2011 the state "pumped $4 billion into the state transportation system to jump-start about 900 projects around Virginia over the next 3 years, with about $2.9 billion in debt to be retired with anticipated federal funds" (Walker, 2011). Now, more than ever, it is imperative that the state use a life-cycle cost process to identify the most correct and timely pavement preservation alternatives in order to optimize usage of the available resources.

PURPOSE AND SCOPE

The purpose of this study was to critically review VDOT's pavement preservation program and provide recommended policy and practice changes that would make the program more effective at every level. The study started with a thorough review of related research and is coupled with an overview of current VDOT practice from both the central office and district perspectives. The research team then used data from VDOT's PMS to model the performance of the most common preservation treatments used in Virginia. An important deliverable is a user friendly selection tool for use at the district level, which is effective in identifying all feasible treatments for pavement sections identified by the PMS as suitable candidates for preventive maintenance, as well as identifying the treatment providing the greatest benefit at the lowest cost for each of these sections. The selection tool was constructed around models of performance for four preventive maintenance treatments: microsurfacing, slurry seal, chip seal, and thin hot mix concrete overlay (THMACO), as well as the reference "do-nothing" deterioration curves.

METHODS

The objectives of the project were met by performing three tasks: state of the practice review, VDOT preventive maintenance performance assessment, and development of preventive maintenance treatment selection tool.

State of the Practice Review

The project started with a compilation of the main findings from various ongoing research projects and current practices in pavement preservation. The complete literature review is included in the Appendix. In addition to summarizing the available preventive maintenance treatments, this review discusses methods used to develop treatment selection tools. The relevant concepts included in the review are performance prediction and modeling, decision trees and matrices, scoring systems, and operations research tools. The literature review also presents case studies of previous approaches used for optimizing pavement preservation treatments.

The first task of the research also included a current practice review of VDOT-specific preventive maintenance. It starts with an overview of VDOT's PMS and follows that system to the point at which it makes recommendations to the districts. A district-level review is then conducted through interviews with staff. The activities of Task 1 concluded with a list of various alternative treatments, their attributes, and characteristics to help decision makers select the most promising treatments for Virginia's roads.

VDOT Preventive Maintenance Performance Assessment

Task 2 reviewed the current pavement treatment practices in Virginia and developed some recommendations for implementation of a preventive maintenance policy. Pavement condition data were obtained from VDOT's PMS. These data were analyzed to develop condition deterioration models for each of the four preventive maintenance treatments recommended in this study for general implementation: microsurfacing, slurry seal, chip seal, and thin hot mix asphalt concrete overlay (THMACO), as well as for those roads that did not receive any preservation treatment, indicated as the "do-nothing" option.

Development of Preventive Maintenance Treatment Selection Tool

Task 3 brought together findings related to treatment feasibility and costs with performance models to produce a district-level treatment selection tool. The user-friendly tool was developed using a Microsoft Excel workbook enhanced with Visual Basic. It applies centrally developed recommendations and allocations for preventive maintenance (PM) with local preferences (e.g., treatment performance & costs) to produce a district-wide preventive maintenance programming aid.

RESULTS

State of the Practice Review

General Concepts

Preventive Maintenance

Maintaining road conditions to acceptable standards with traditional pavement maintenance approaches can be quite costly (Zaniewski and Mamlouk, 1999). 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" (Geiger, 2005). Pavement preservation is a general category of road maintenance that consists of three components: minor rehabilitation, routine maintenance, and preventive maintenance (Geiger, 2005).

Although the terms "pavement preservation" and "preventive maintenance" are often used interchangeably, preventive maintenance is in fact a subset of pavement preservation. Preventive maintenance maintains the functional condition of roadway systems, without improving their structural capacity, by strategically applying cost-effective treatments (Peshkin and Hoerner, 2005). Preventive maintenance seals the pavement surface and prevents water from infiltrating into the pavement structure. These treatments are often applied to pavements in relatively good condition and prolong pavement life by maintaining the pavement in an acceptable state for a longer period of time. Preventive maintenance allows pavements to be maintained during times of reduced funding (Hicks et al., 1999). 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" (Zaniewski and Mamlouk, 1999). This concept is illustrated in Figure 1.

With growing concerns about the environmental impact of our built infrastructure, sustainability is becoming a common theme among road agencies. The principle of sustainability requires consideration of economic, social, and environmental progress while meeting human needs for the present and the future (Zietsman, 2011).

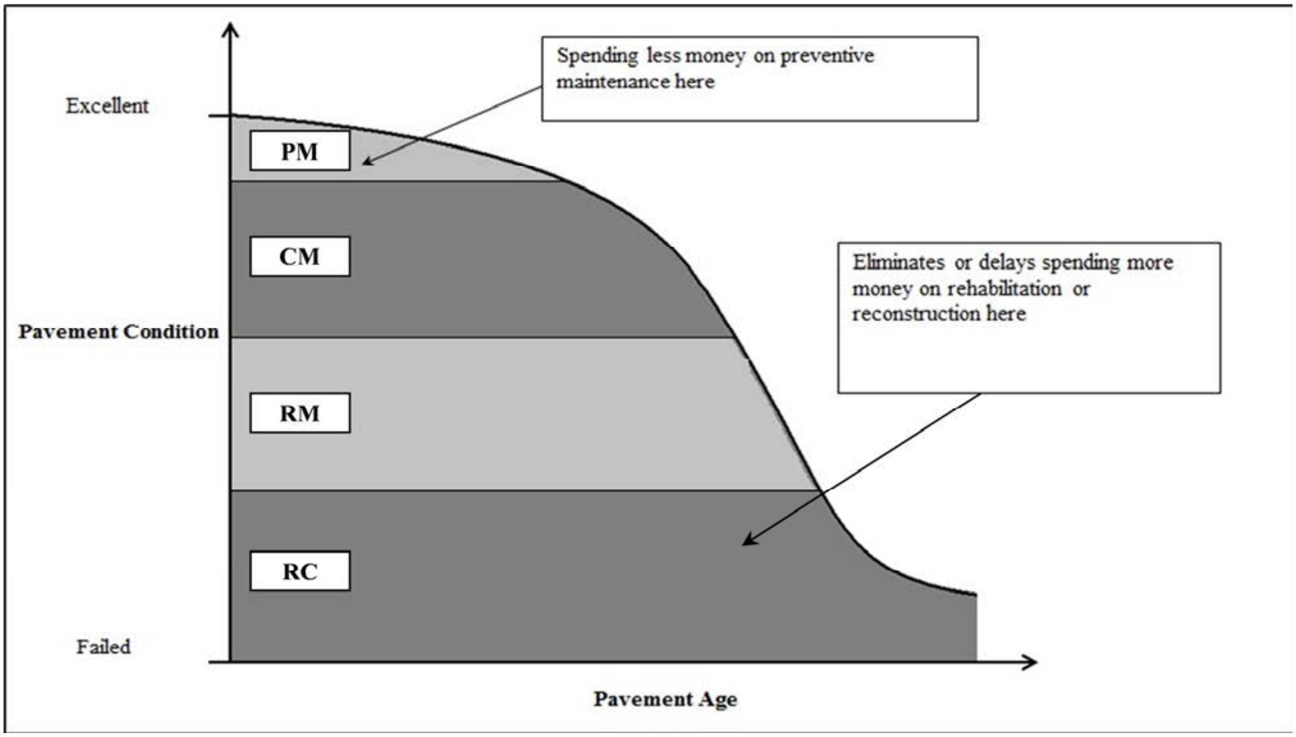

Figure 1. Preventive Maintenance Benefits (from FHWA, 2007)

The criteria outlined in Alkins et al. (2008) identify the characteristics of a sustainable pavement to include the following:

- optimized use of available resources
- reduced energy consumption, greenhouse gas (GHG) emission, and pollution
- improved health and safety
- increased user comfort.

Preventive maintenance treatments satisfy these criteria. Also, when compared to traditional treatments (such as milling with hot mix asphalt overlays), preventive maintenance treatments are generally thinner, have faster application rates, and are less disruptive (Chan et al., 2011). These benefits, alongside the better life-long performance of pavements that are part of a preventive maintenance program, support the idea of preventive maintenance as a tool for increasing the sustainability of our transportation infrastructure.

However, some agencies still avoid preventive maintenance treatments on high-volume roads because of concerns regarding the liability associated with the potential failure of the treatment. Furthermore, preventive treatments applied to high-volume roads may not be as effective as treatments applied to low-volume roads because high-volume roads may experience a faster rate of deterioration. 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 (Smith and Peshkin, 2011).

Popular preventive maintenance treatments include the following (described in more detail in the Appendix):

- 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

In 2001, the American Association of State Highway and Transportation Officials (AASHTO) published a guide for pavement management that outlined 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 PMS as "a set of tools used to assist decision-makers at all levels in making better and more informed decisions" (AASHTO, 2001).

A PMS is an important tool in the development of preventive maintenance policies. It can demonstrate the key benefit to preventive maintenance: preventing potentially costly rehabilitation by maintaining good pavement condition. One possible benefit of integrating PMS with preventive maintenance is the possibility of optimizing the treatment selection 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 (Zimmerman and Peshkin, 2003).

Current Practice—VDOT Central Pavement Management

Pavement Management

VDOT currently uses a pavement management software system developed by Agile Assets (Agile Assets, 2012). 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 pavement 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 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.

VDOT's Central Office Maintenance Division generates reports from VDOT's PMS that provide maintenance targets for each district. Recommended budget and number of lane-miles are provided for each maintenance category (DN, PM, CM, RM, and RC). The district maintenance engineer uses these recommendations, along with the unconstrained analysis, to select pavements for maintenance and treatments to be applied.

Maintenance Categories

The total roadway system under the responsibility of the VDOT 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 (Heltzel, 2010). Table 1 outlines the current maintenance activities for different maintenance categories used in VDOT's PMS and a brief description of the types of maintenance activities included in each category.

Table 1. VDOT Maintenance Activities for Interstate and Primary Pavements under Different Categories (Chowdhury, 2008)

Activity Category	Activities
Do Nothing (DN)	N/A
Preventive Maintenance (PM)	Surface Treatment (Chip Seal, Slurry Seal, Microsurfacing, Ultra-thin bonded wearing course, etc.)
	Crack Sealing
	Minor Patching (< 5% Pavement Area) Surface Patching (Depth of ≤ 2")
Corrective Maintenance (CM)	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)	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)
Rehabilitation / Reconstruction (RC)	Mill, Break, and Seat and AC Overlay (9-12" overlay)
	Reconstruction

AC = Asphalt Concrete.

Each year, pavement condition data are collected by multi-function data collection vehicles with cameras that take pictures of the pavement to capture cracking and laser sensors to capture roughness and rutting. Pavement condition is obtained annually for interstate and primary routes, and the PMS is updated with the most recent condition data. The asphalt pavement distresses that are catalogued include transverse cracking, longitudinal cracking, reflective transverse cracking, reflective longitudinal cracking, alligator cracking, longitudinal joint cracking, patching, potholes, delamination, bleeding, and rutting.

VDOT uses three condition indices to rate pavement distresses. The first index is the Load-Related Distress Rating (LDR), which measures pavement distresses caused by traffic loading. The second index is the Non-Load-Related Distress Rating (NDR), which measures pavement distresses that 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 (McGhee, 2002). In addition to storing the individual distress data, the PMS calculates and stores the LDR, NDR, CCI, and the International Roughness Index (IRI) for all sections.

The pavements are classified into the following general types: Bituminous over Jointed Concrete Pavement (BOJ), Bituminous over Continuously Reinforced Concrete Pavement (BOC), full-depth 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 in the *poor* and *very poor* categories. The pavement condition categories for interstate and primary pavements based on CCI and IRI values are shown in Table 2. The statewide performance targets for interstate and primary roads are ≤ 18% deficient for CCI and < 15% deficient for IRI.

Table 2. Interstate and Primary Pavement Condition Categories Based on CCI and IRI Values (Heltzel, 2010)

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

Unconstrained Maintenance Needs

VDOT follows a two-phase process, illustrated in Figure 2, to determine pavement maintenance needs for interstate and primary roads. The first phase uses distress data and the pavement's CCI 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 (Chowdhury, 2008).

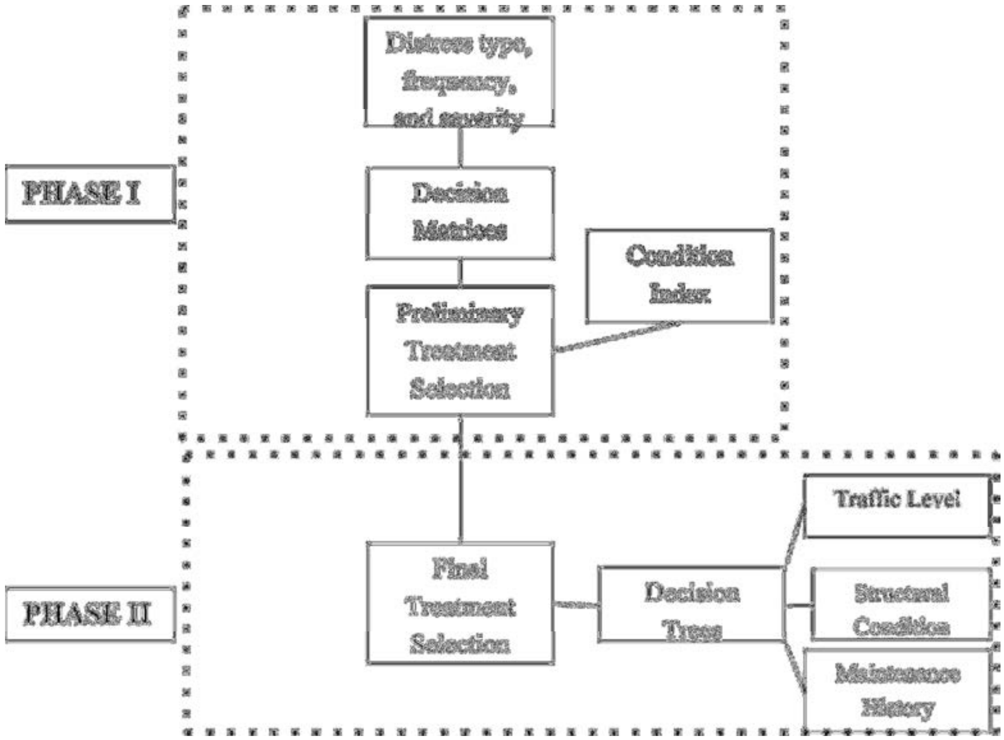

Figure 2. Process for Unconstrained Maintenance Needs Assessment (Chowdhury, 2008)

Decision Matrices

VDOT uses several decision matrices for developing maintenance treatment plans. The specific decision matrix used for each pavement depends upon the type of distresses present, their severity, and their 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 3. Preliminary maintenance treatment selection is made after both the CCI triggers and these decision matrices have been consulted. A complete list of all the decision matrices specific to preventive maintenance selection is available in Chowdhury (2008).

Table 3. VDOT Decision Matrix for Transverse Cracking (Chowdhury, 2008)

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

CCI Triggers for Preventive Maintenance

In addition to the 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 (Chowdhury, 2008). In the secondary system, pavements that have an asphalt concrete (AC) surface are considered plant mix, but those having only an asphalt surface treatment (single, double, etc.) are considered non-plant mix. Preventive maintenance treatments are mostly used for pavements with a CCI of 60 or higher, where it has been determined that a do-nothing alternative is not enough but also where a corrective maintenance alternative is not warranted. Figure 3 summarizes the typical ranges of application of the different maintenance categories for each road classification. It should be noted that the application of preventive maintenance treatments outside of the recommended ratings generally results in sub-optimal treatment performance.

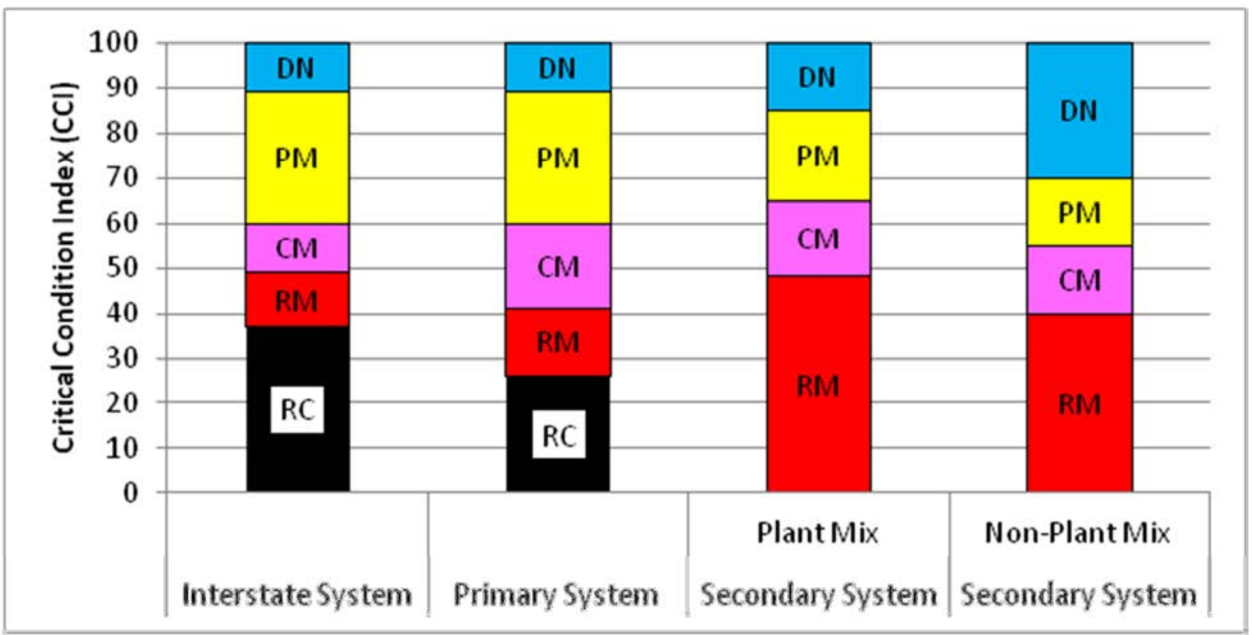

Figure 3. Maintenance Activities for Each Road System

Decision Enhancements

As outlined in Figure 2, the preliminary treatment selection is enhanced using decision trees that incorporate traffic, structural condition, and maintenance history. The decision tree for preventive maintenance on interstate BIT routes is shown in Figure 4.

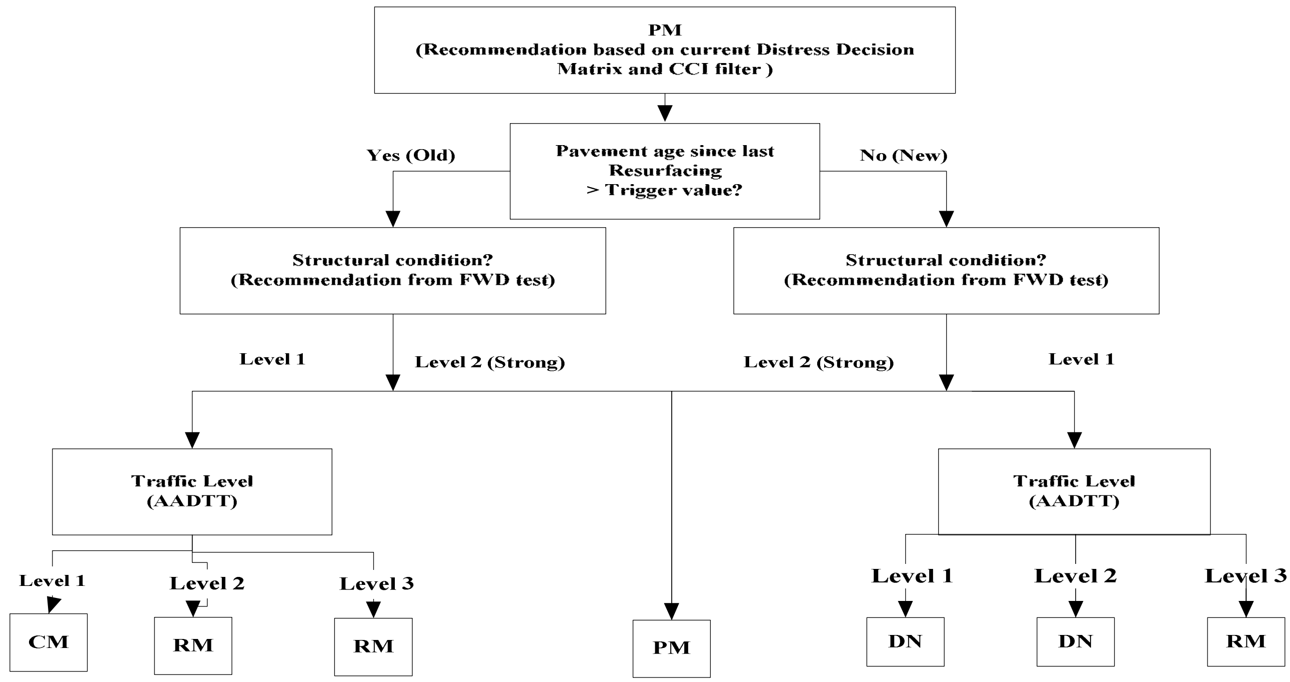

Figure 4. VDOT Decision Tree Enhancements for Preventive Maintenance on BIT Interstate Routes

Cost Estimates

The VDOT Central Office estimates the costs of different types of maintenance using material cost bids from previous projects, adjusted for inflation. The estimated costs of the various maintenance categories used by the VDOT Central Office at the time of the study are shown in Table 4. It should be noted that the historical cost data for the preventive maintenance category include mainly crack sealing and patching.

Table 4. Preventive Maintenance Central Office Cost Estimates (Chowdhury, 2008)

Treatment	Cost per Lane-Mile for Interstate	Cost per Lane-Mile for Primary
PM	$6,975	$6,977
CM	$71,817	$59,686
RM	$180,631	$153,229
RC	$507,958	$480,494

Current Practice—District Pavement Management

VDOT defines a deficient pavement as one with a CCI value below 60. The statewide target for interstate and primary route condition is to have less than 18% of the pavements rated as deficient (Heltzel, 2010). The deficiency percentages for each district are shown in Figure 5.

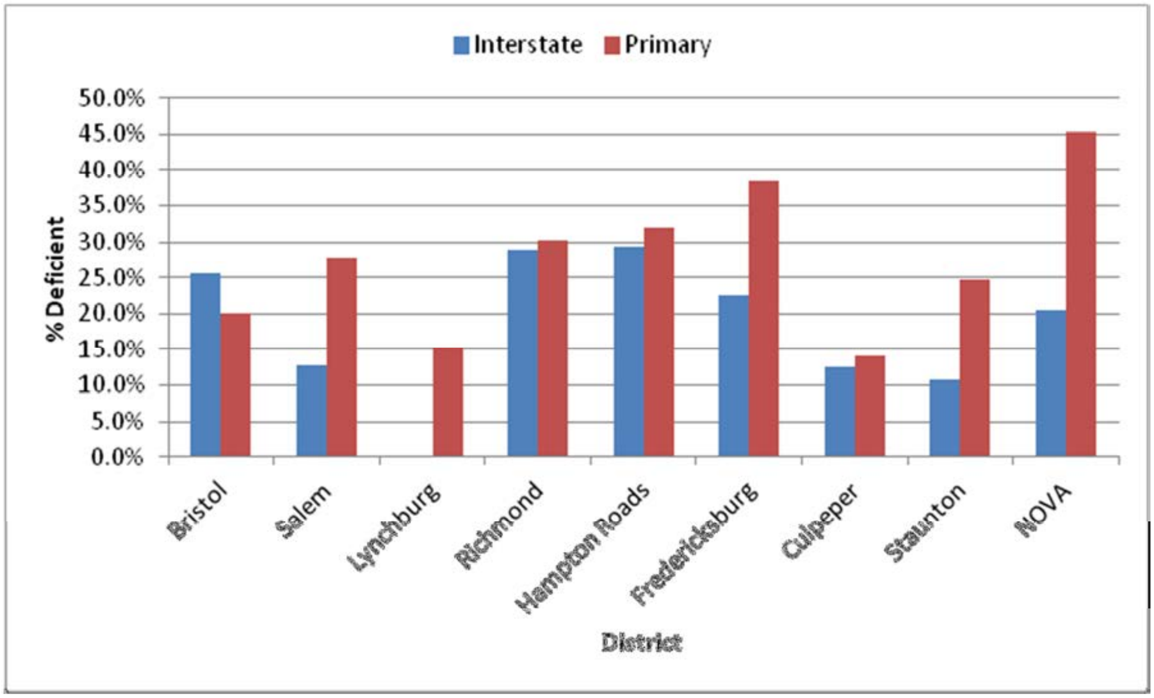

Figure 5. Deficiency Percentages by District for Interstate and Primary Routes (Heltzel, 2010)

The figure shows that each district has different levels of pavement deficiency. There are many factors that can contribute to different overall pavement performance from district to district. While many of these factors are uncontrollable (e.g., climate, traffic), some differences may result from dissimilar approaches to pavement maintenance, as there is currently no statewide preventive maintenance policy.

To explore how preventive maintenance policy varied around the state, three districts were selected for closer evaluation: Salem, Richmond, and Northern Virginia. Maintenance and materials engineers for these regions were interviewed to identify and document the current practices at the district level. These interviews allowed a comparison between in-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. Its office serves more than 650,000 citizens and 14 cities and towns within its boundaries. The district comprises 12 counties and has 4 residency offices. The total number of lane-miles in this district is 17,966, including 490 lane-miles of interstate roadways, 2,668 lane-miles of primary roads, and 14,701 lane-miles of secondary roads (VDOT, 2012a). Table 5 summarizes Salem's percentage of deficient roads in its interstate and primary road networks.

On October 21, 2011, Jeff Wright, Pavement Manager, was interviewed as part of this project. He indicated that preventive maintenance treatments are selected based on the pavements' CCI and year of paving. Preventive maintenance is performed on road sections with a CCI of 85 or higher. The data used for scheduling are obtained from the Central Office Maintenance Division.

Table 5. Percentage of Salem District's Deficient Interstate and Primary Roads by County (Heltzel, 2010)

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

District personnel prioritize the treatment of interstate and primary roads. The residencies administer treatment of secondary roads. Modified single seals, an application involving two layers of aggregates, are the typical treatment used for chip seals. Slurry seals are used on higher-volume secondary roads, but not on primary roads because they take too long to cure. The typical preventive maintenance treatments currently being used in the Salem District are summarized in Table 6.

Table 6. Preventive Maintenance Treatments in Salem District

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

Richmond District

The Richmond District is located in central Virginia. Its 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, including 1,319 lane-miles of interstate roadways, 3,417 lane-miles of primary roads, and 13,750 lane-miles of secondary roads (VDOT, 2012b). Table 7 summarizes the percentage of deficient roads in Richmond's interstate and primary road network.

On November 30, 2011, William Hughes, Pavement Management Engineer for the Richmond District, granted an interview for the project. He stated that preventive maintenance is applied to roads with a 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.

Table 7. Percentage of Richmond District's Deficient Interstate and Primary Roads by County (Heltzel, 2010)

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

As in the Salem District, the interstate and primary roads are managed by district personnel, but secondary roads and subdivisions are maintained through the residencies. The typical preventive maintenance treatments currently being used in the Richmond District are summarized in Table 8.

Table 8. 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 micro"	Primary roads
Crack seal	--	Interstate
Cape seal	--	Secondary roads

Northern Virginia (NOVA) District

The Northern Virginia District is located in the Washington, D.C., metropolitan area. Its 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, including 684 lane-miles of interstate roadways, 1,549 lane-miles of primary roads, and 10,343 lane-miles of secondary roads (VDOT, 2012c). Table 9 summarizes the percentage of deficient roads in NOVA's interstate and primary road network.

Table 9. Percentage of NOVA District's Deficient Interstate and Primary Roads by County (Heltzel, 2010)

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

On November 22, 2011, Rob Wilson, the NOVA District Pavement Engineer, was interviewed for this project. He indicated that preventive maintenance treatments may be applied to roads with a CCI of 80–89. Preventive maintenance and corrective maintenance (e.g., crack sealing and minor patching) are an option for roads with a CCI of 70–79. The typical pavement age for application of preventive maintenance treatments is 3 to 5 years for high-volume roads and 5 to 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: conditions can deteriorate very rapidly, making scheduling more difficult. The typical preventive maintenance treatments currently being used in the Northern Virginia District are summarized in Table 10.

Table 10. 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 on the various road classes across districts is shown in Table 11. The CCI triggers for preventive maintenance used by the three districts are compared in Table 12.

Table 11. Treatment Placement by District

Treatment	Placement		
	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 12. 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 built into the PMS. These are recommendations for general maintenance categories, however, and districts must use their experience and judgment to select the specific treatment types and pavement sections to be treated. The responses received from the Salem, Richmond, and NOVA districts revealed that each district has developed its own preventive maintenance policy over time and that 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. The NOVA District applies slurry seals to primary and secondary roads, but it does not use microsurfacing. Additionally, the CCI triggers for preventive maintenance vary between districts.

General Experience and Expectations

This investigation highlighted the need for a formal preventive maintenance policy that builds on the central office's recommendations and uses distress type and severity, pavement age, network classification, and traffic to develop preventive maintenance treatment selections that are consistent across districts.

The effectiveness of each treatment for specific distress types was obtained from the literature. Table 13 summarizes expected life, life extension, and unit costs of preventive maintenance treatments that were found in the literature, modified by those that have been more successfully used in Virginia and some that appear promising (Peshkin et al., 2011; COLAS, 2013).

Table 13. Expected Performance and Cost of Preventive Maintenance Treatments

Treatment	Expected Performance		Estimated Unit Cost
	Treatment Life (years)	Life Extension (years)	
1. Fog seal	N/A	N/A	$0.30–$0.42/yd^2
2a. Crack filling (flush fill, non-working cracks)	2–4 (3–5)	N/A	$0.10–$1.20/ft. $0.20–$0.25/ft.
2b. Crack sealing (overband fill, working cracks)	3–8	2–5	$0.75–$1.50/ft.
3. Rejuvenators	2	N/A	$0.50–$0.68/yd^2
4. Slurry seal	3–5 (4–7)	4–5	$1.15–$1.50/yd^2 $0.75–$1.00/yd^2
4. Microsurfacing ● Single ● Double	3–7 3–6 4–7	 3–5 4–6	 $2.15–$2.50/yd^2 $1.50–$3.00/yd^2
5. Chip seal ● Single (conventional) ● Single (polymer modified) ● Double	 2–4 3–7 5–10	 5–6 8–10	 $1.50–$1.75/yd^2 $1.50–$2.00/yd^2 $2.00–$4.00/yd^2
6. FiberMat® (polymer-modified emulsion with fibers) ● Type A ● Type B (SAMI)	7–10	N/A	$3.25–$5.00/yd^2
7. Cape seal ● Chip seal + Slurry type 1 ● Chip seal + Slurry type 2 ● Chip seal + FiberMat® + Slurry	5–7	N/A	 $3.25–$3.75/yd^2 $5.00–$6.00/yd^2
8. Ultra-thin friction course 0.4”–0.80”	7–12	N/A	$4.00–$6.00/yd^2
9. Ultra-thin HMA overlay 0.625”–0.75”	4–8	N/A	$2.00–$3.00/yd^2
10. UltraWear^{TM} (formerly NOVACHIP) ● Type A 3/8” ● Type B 9/16” ● Type C 3/4”	10+	N/A	
11. 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
12. Thin HMA O/L and cold milling	5–12	N/A	$5.00–$10.00/yd^2

HMA = hot mix asphalt, O/L = overlay, N/A = not applicable.

Performance of Preventive maintenance treatments Used in Virginia

Preventive Maintenance Treatments

VDOT's PMS contains historical performance data on preventive maintenance treatments that are commonly used in Virginia. These data were used to develop Virginia-specific treatment performance models for preventive maintenance on BIT, the most common pavement type. The performance of four preventive maintenance treatments were considered using data from the interstate and primary systems for chip seals, slurry seals, microsurfacing, and THMACO.

Linear regression models were used to develop the performance curves. The linear model allows for easier use in follow-up application (see later discussion on benefit calculations) with minimal reduction in the accuracy that might be provided by more complex models. As an example, Figure 6 presents a quick comparison between the model form as incorporated in VDOT's PMS and a simple linear model. This comparison shows that the linear model is an adequate representation of expected pavement performance.

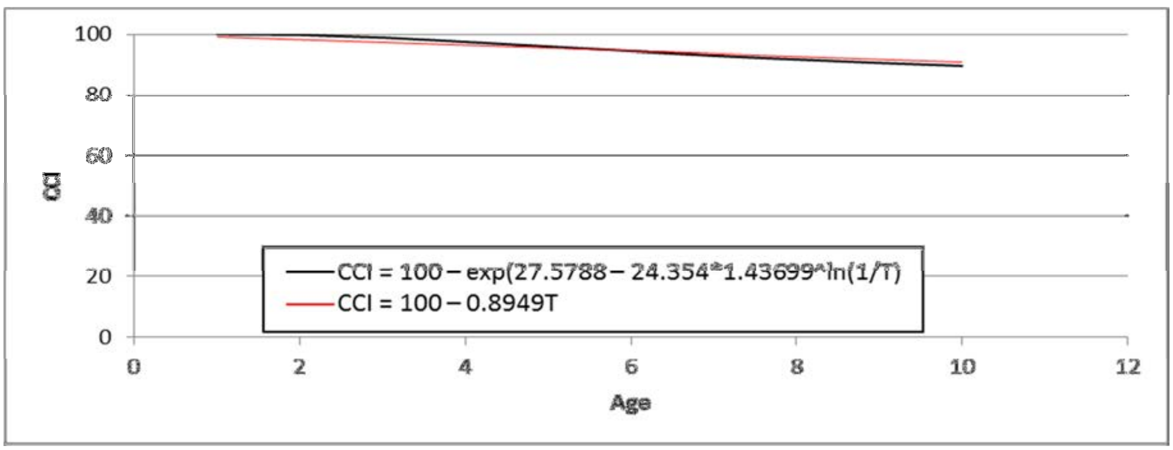

Figure 6. Comparison between VDOT Model and Linear Model

Of the historical information from the PMS, 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 only 22 records available for THMACO. Because the microsurfacing dataset was so large, these data were divided according to type of network: interstate or primary.

Some sections had CCI values of -1, suggesting that the data for these sections were not collected. These null sections were removed. After the data were inspected, it was seen that pavement condition seemed to improve after 10 years. This was attributed to the possible unrecorded application of treatments to pavements. Records suggesting that the existing treatment was older than 10 years were also deleted from the analysis.

Based on recommendations from VDOT Central Office personnel, an outlier analysis was performed to remove any outliers in the data. Data were grouped according to pavement age, and the standard deviation and average condition were computed for each group. A standard normal distribution was assumed and the z score was computed. Any pavement section having z

< -1.96 or z >1.96 was removed from the analysis. Linear regression was then performed to obtain the expected performance of each preventive maintenance treatment. A summary of all the models developed is listed in Table 14. The resulting models are overlapped with the data used for their development in Figures 7 through 11.

Table 14. PM Treatment Models

PM Treatment	Model	R^2
Microsurfacing interstate	CCI = 100 – 4.7954*Age	0.0879
Microsurfacing primary	CCI = 100 – 6.3780*Age	0.2179
Slurry seal	CCI = 100 – 4.9392*Age	0.3000
Chip seal (1)	CCI = 100 – 3.8905*Age	0.0573
THMACO (1)	CCI = 100 – 0.8422*Age	0.5775

(1) The estimated performance for chip seal and THMACO treatments is based on a very limited number of data points and thus, these models may not be representative of the typical performance of these treatments. In particular, the THMACO model is based on only a few demonstration projects placed on very strong pavement sections and thus it is very unlikely that this treatment will perform similarly on more typical pavements.

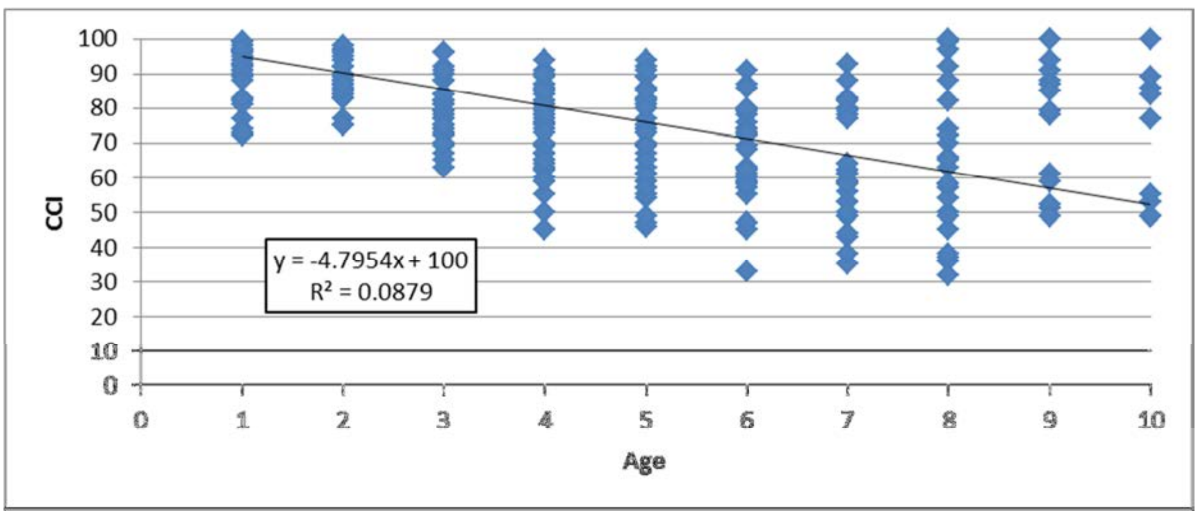

Figure 7. CCI versus Age for Microsurfacing on Interstate Pavements

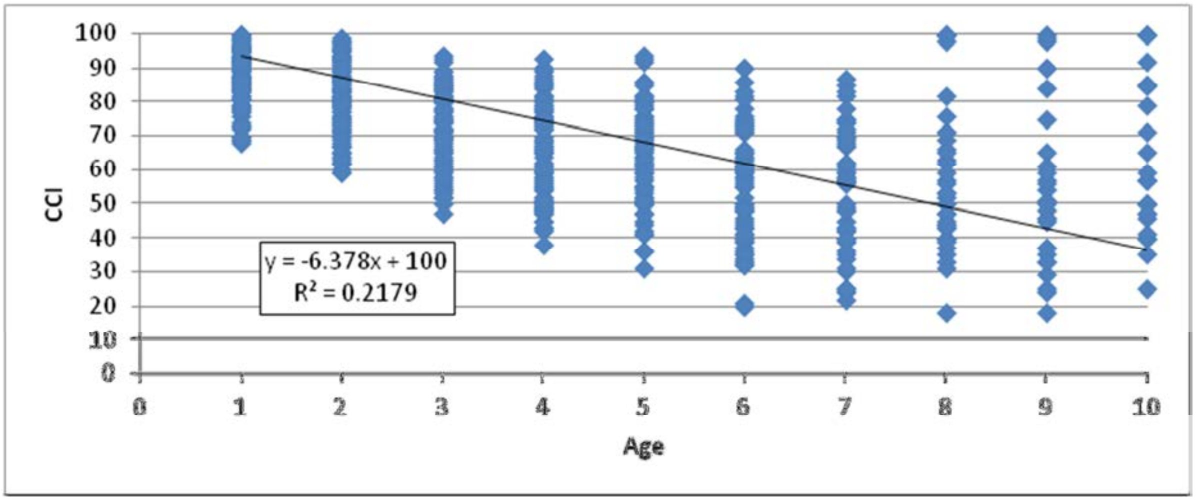

Figure 8. CCI versus Age for Microsurfacing on Primary Pavements

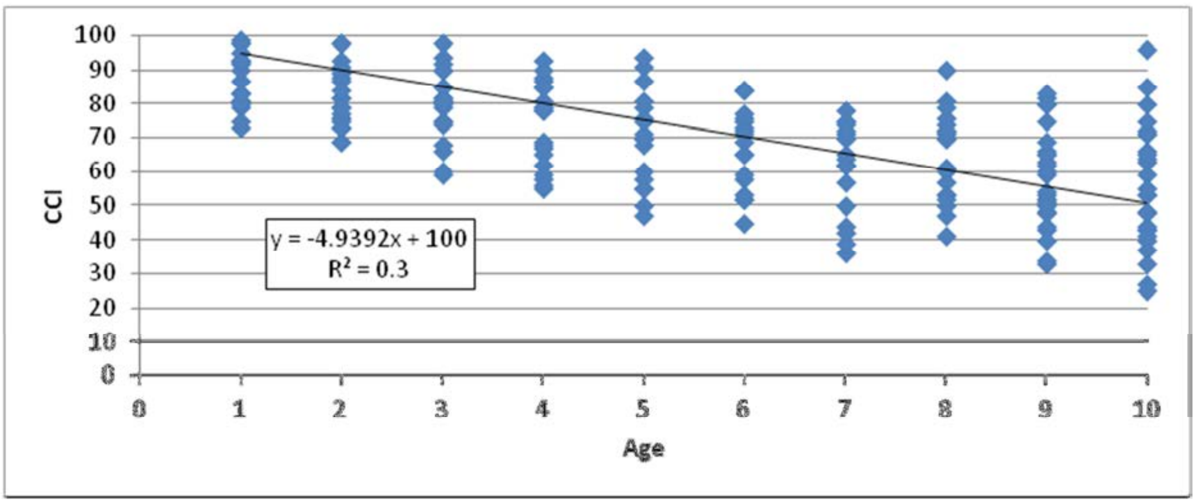

Figure 9. CCI versus Age for Slurry Seal

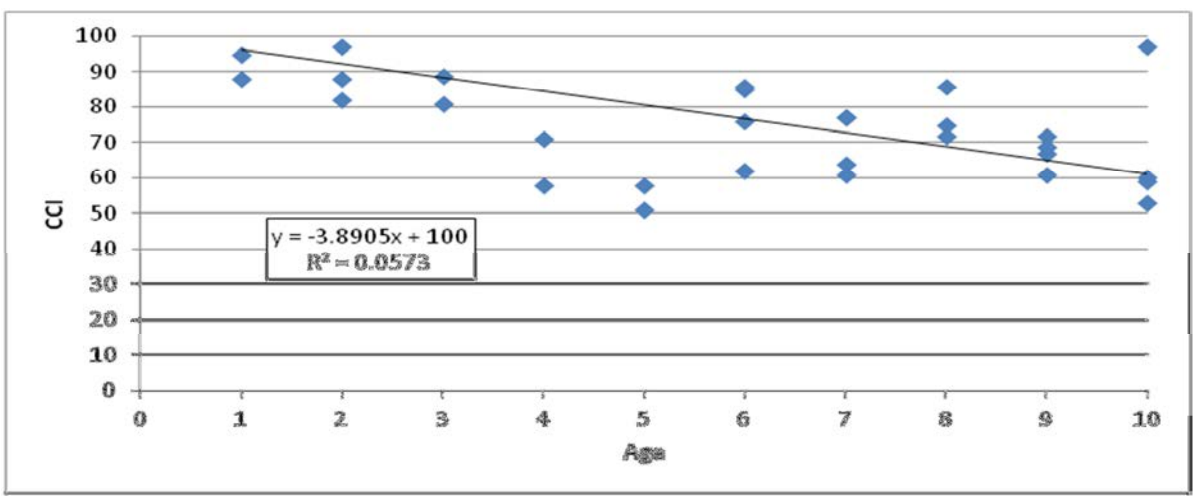

Figure 10. CCI versus Age for Chip Seal. The number of data points available for chip seals is very limited and thus, the model may not be representative of the performance of this treatment on typical pavements.

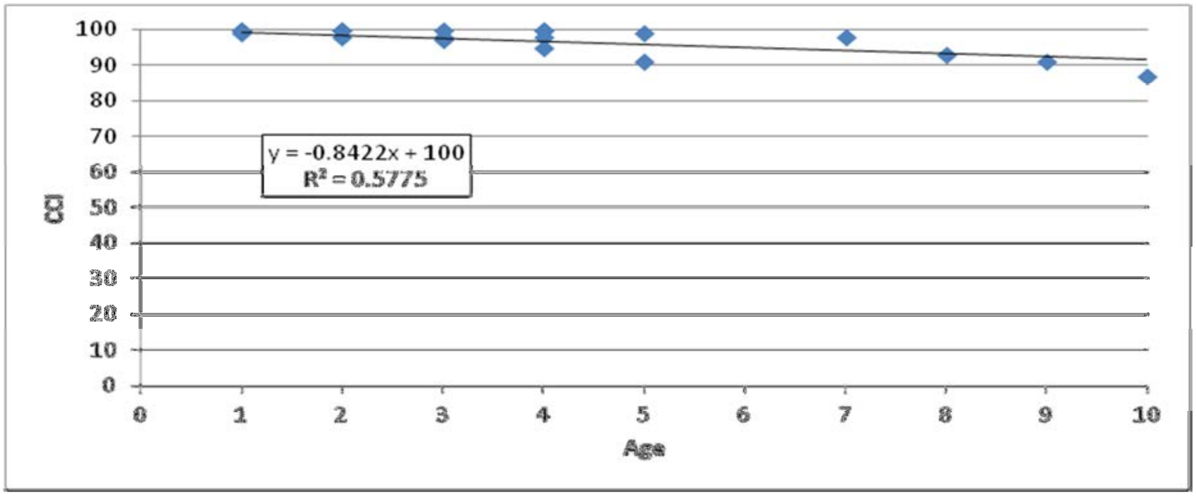

Figure 11. CCI versus Age for THMACO. The number of data points available of THMACO is very limited (from a few demonstration projects placed on very strong pavement sections) and thus, the model may not be representative of the performance of these treatments on typical pavements.

The models developed as part of this analysis were counterintuitive. Microsurfacing was expected to perform better than slurry seals because microsurfacing uses higher quality aggregates as well as a polymer-modified asphalt emulsion. However, the models showed that the rate of deterioration for microsurfacing on primary routes was faster than the rate of deterioration of slurry seals. It is believed that microsurfacing may have been applied to pavements in worse condition than those receiving slurry seals, rendering the treatment less effective. However, this hypothesis could not be confirmed because the condition data from before treatment application were not readily available. It is believed that updating the data for maintenance history and removing from the analysis the pavements that have known structural issues would improve the reliability of the models. However, the models developed as part of this report were used in the selection tool (to be discussed later).

Preventive Maintenance Treatment Model Revision

After consulting with the Central Office Maintenance Division, the data were revisited and the models were rerun. The data were filtered as in the previous section: the sections having a CCI value of -1 or more than 10 years of service were removed, as well as the outlier. An additional filter was then applied, which was used in the analysis previously developed for VDOT (Stantec and Lochner, 2007). This filter is outlined in Table 15.

Table 15. Maximum CCI Values for Pavement Age Groupings (Stantec and Lochner, 2007)

Age (Years)	Maximum Value
0 – 5	100
5 – 10	95
10 – 15	90
15 – 20	85
20+	80

Next, the average CCI value for each pavement age was plotted and linear regression was used to determine the expected performance of each treatment. A summary of all the models developed is listed in Table 16.

Table 16. Revised PM Treatment Models

PM Treatment	Model	R^2
Microsurfacing interstate	CCI = 100 – 4.6987*Age	0.2520
Microsurfacing primary	CCI = 100 – 5.6234*Age	0.5572
Slurry seal	CCI = 100 – 5.1117*Age	0.7051
Chip seal	CCI = 100 – 9.8558*Age	0.8702
THMACO	CCI = 100 – 1.0933*Age	0.8075

These revised models show a more reasonable trend for treatment performance. As expected based on the review of literature, THMACO and microsurfacing had the highest level performance, while slurry seal and chip seal had the lowest level of performance.

Finally it must also be noted that the new models were not used in the pilot implementation of the preventive-maintenance project selection tool. However, the analysis demonstrates that models can be improved with more aggressive filtering and outlier analysis. The models should be further refined as data quality is continuously improved over time. Each year the dataset grows larger with new pavement evaluation surveys, and the paving history is continually updated within the PMS, allowing for more accurate pavement age information.

Do-Nothing Alternatives

In order to quantify the additional benefit of using preventive maintenance, it is important to be able to quantify the performance of the pavement sections that have not received a treatment. Instead of developing new models for these roadway sections, a simplification of the existing models developed specifically for VDOT (Stantec and Lochner, 2007) was used. Models were available for each type of pavement (BIT, BOC, BOJ, CRC, and JRC), pavement functional class (interstate, primary), and type of last-performed maintenance (CM, RM, or RC). For the PMS analysis, the default model assigned to pavement sections is the CM model. Linear approximations for these models were obtained for interstate and primary routes on BIT. The linear model allows for a general computation of benefit with minimal reduction in the accuracy provided by more complex models. A sample comparison between the accepted VDOT model and a linear model is shown before in Figure 6. This comparison shows that the linear model is an adequate representation of expected pavement performance expressed by the VDOT model.

The linear do-nothing models are presented in Equation 1 for interstate routes and Equation 2 for primary routes.

$$\mathrm{CCI} = -5.20*\mathrm{Age} + 100 \qquad \text{(Interstate)} \qquad \text{(Eq. 1)}$$

$$\mathrm{CCI} = -3.80*\mathrm{Age} + 100 \qquad \text{(Primary)} \qquad \text{(Eq. 2)}$$

Preventive Maintenance Treatment Selection Methodology

Framework for the Treatment Selection Tool

Based on the review of existing practices, 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. The treatment selection tool was developed in two parts: (1) feasible treatment identification, and (2) the district-wide selection. The framework of the treatment selection tool is presented in Figure 12.

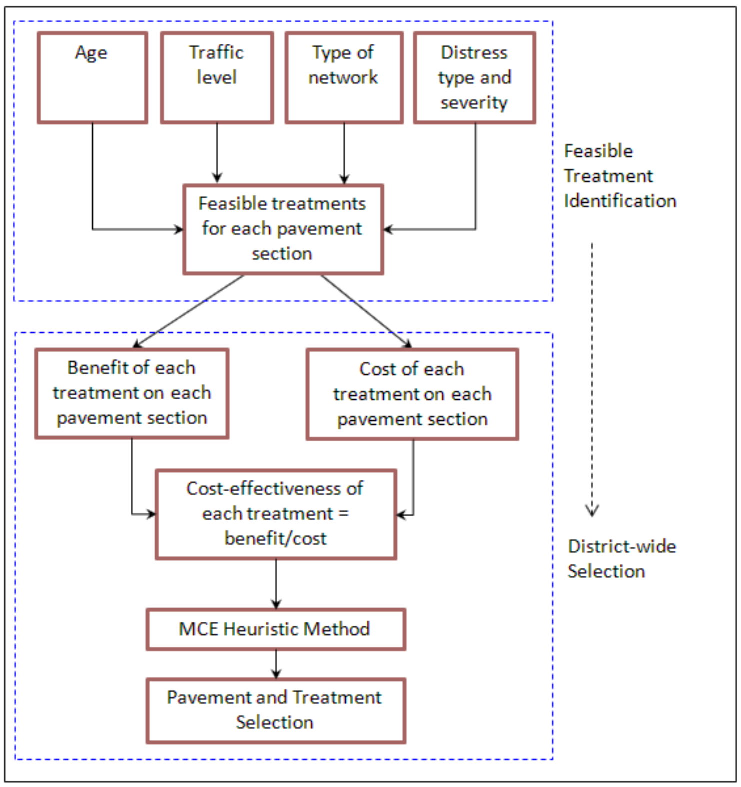

Figure 12. Overview of Treatment Selection Tool

Treatment Feasibility

Treatment feasibility is established based on the pavement section's age, traffic level, type of network, and distresses used in the VDOT decision matrices: alligator cracking, transverse cracking, rutting, and patching. The treatment properties, listed in Table 17, were based on those found in the literature review. The expected treatment life and cost of each treatment from the most recent SHRP 2 study (Peshkin et al., 2011) are presented in Table 18 along with current unit costs obtained from VDOT.

Table 17. Treatment Feasibility Matrix

Treatment	Type of Network	Age		Traffic Level	Alligator Cracking Severity	Transverse Cracking Severity	Rutting Severity	Patching Severity
		Min	Max					
Chip Seal[a]	Primary	5	8	All	1	1	1	1
Slurry Seal[a]	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

[a] 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 under high speed traffic (Wade et al., 2001). Slurry seals are characterized by unpredictable break and cure times (Peshkin et al., 2011), which could translate into unacceptable extended lane closures.

Table 18. Treatment Life and Estimated Cost (Peshkin et al., 2011)

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

Benefit and Cost Calculations

The benefit of each treatment on each section is 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 13. This benefit cutoff value was assumed to be 60 based on the VDOT deficient pavement criterion, which considers pavements with a CCI below 60 to be deficient. The benefit computation is shown in Equation 3:

$$Benefit = (Lane - miles) \times \left[\frac{(d-60)(c-a)}{2} - \frac{(e-60)(b-a)}{2}\right] \qquad \text{(Eq. 3)}$$

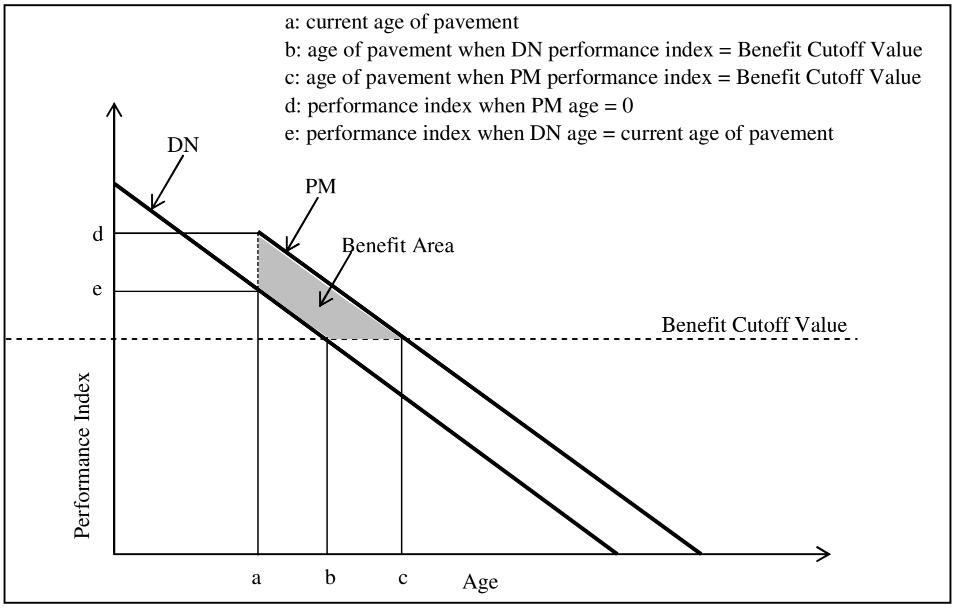

Figure 13. Computation of Treatment Benefit

The cost of each treatment on each maintenance section is calculated using specified unit costs and pavement area as shown in Equation 4:

$$\text{Treatment Cost } = (\text{lane} - \text{miles}) \times (\text{lane width}) \times (\text{unit cost}) \qquad (\text{Eq. } 4)$$

The cost-effectiveness of each treatment on each maintenance section is computed using the benefit-cost ratio (BCR), which, as its name suggests, is the ratio of benefit (estimated by the area computed using Equation 6) to cost.

The marginal cost-effectiveness (MCE) method is then used to perform pavement and treatment selection. This heuristic was selected against a true optimization approach because it can be implemented in a simple Excel spreadsheet. Each possible combination of pavement section and treatment is computed and listed. For each pavement section, the treatments are sorted in ascending order based on their cost. The increase in cost and increase in benefit are both computed for each new treatment on each section. If there is a negative value for increase in benefits—in other words, a decrease in benefit for an increase in cost—this treatment option is removed from consideration. The MCE is then computed as shown in Equation 5:

$$\text{MCE} = (\text{Increase in Benefit}) \,/\, (\text{Increase in Cost}) \qquad (\text{Eq. } 5)$$

The corrected MCE is then computed as the lower value between the treatment's BCR and MCE. All options are then sorted in descending order based on the corrected MCE.

District-level Pavement Preservation Treatment Selection Tool

The framework presented in the previous section was implemented in an Excel spreadsheet. The selection tool requires certain user inputs in order to develop treatment recommendations for each section and to provide a prioritized list of pavements that can be used by the districts to aid in their maintenance programming. The inputs required for the tool include the following:

- Estimated performance
  - Preventive maintenance treatment
  - Do-nothing
- Current-year condition data
- Cost data
- Central Office recommendations - total preventive maintenance lane-miles and district budget as derived from PM lane-miles.

The first decision window in the selection tool lets the user address expected performance. It provides the choice to use default do-nothing models and the developed treatment performance models (see earlier discussion), or to input new models. As an example, the model selection window for primary routes is shown in Figure 14.

The current year's pavement condition is obtained from the PMS for each district. Eligible candidates for preliminary consideration for preventive maintenance include all pavements that satisfied the PMS requirements for PM. The results from the PMS decision matrix analysis are obtained for all sections recommended for PM on BIT pavements. After exporting these data from the PMS and saving them in a spreadsheet, they are then imported into the treatment selection tool.

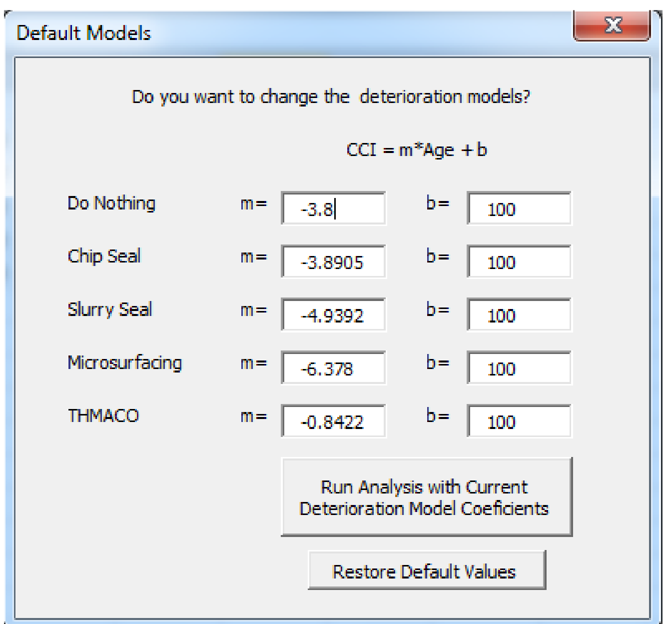

Figure 14. Model Selection Window

The current (default) unit costs for the treatments were presented in Table 15. The selection tool gives the user the option to input new cost data based on local market prices. This flexibility is particularly useful because treatment costs vary among districts and over time. The unit cost input window is shown in Figure 15. This window is automatically populated with default model values. Users have the option to change these values and later restore the default values.

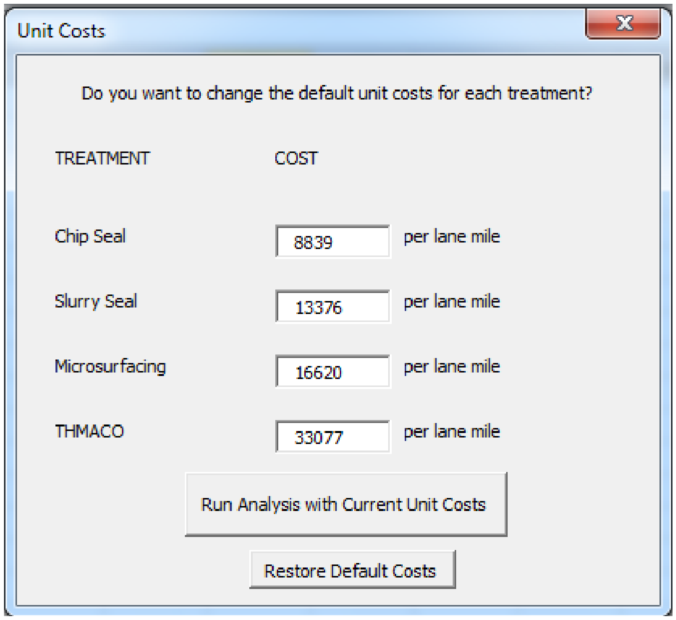

Figure 15. Unit Cost Input Window

The VDOT Central Office provides recommendations for each district regarding recommended lane-miles for each maintenance type (DN, PM, CM, RM, and RC). The budget available for this work can be obtained from estimated lane-mile costs of each treatment. The selection tool gives the user the ability to input these Central Office recommendations into his/her district.

Pilot Implementation of the District-Wide Preventive Maintenance Program

Pilot Implementation Exercise

Loaded with district-specific input the selection tool generates output regarding all possible feasible treatments, the cost-effectiveness of treatments, and the recommended program for the district based on the MCE computations. To test the practicality and functionality of the treatment selection tool, it was run for each district and each roadway classification (interstate and primary) using the 2011 data and the original deterioration curves to obtain a prioritized list of pavement sections and their respective treatments.

If a treatment is identified as being feasible for application on a pavement section, the program assigns it a value of "Y." If the treatment is not feasible, it is assigned a value of "N." An example of the treatment feasibility output is presented in Figure 16.

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

Figure 16. Treatment Feasibility

As part of the MCE process, the program then computes the benefit and cost for each feasible treatment on each pavement section. Each combination of pavement section and feasible treatment is listed and the treatments sorted in ascending order of cost. The benefit-cost ratios are computed for each combination, as well as the incremental cost and benefit for each alternative treatment on each section. Any treatments that result in a higher cost but lower benefit are removed from consideration for that section. An example of this output is presented in Figure 17.

The program then computes the MCE as the change in benefit divided by the change in cost. The corrected MCE is calculated as stated in Equation 6.

$$MCE_{corrected} = \min(BCR, MCE) \qquad \text{(Eq. 6)}$$

The software then sorts the list of pavement and treatment combinations in descending order of corrected MCE values and selects sections until the allocated budget is exhausted. If an alternate treatment for a section that is already on the list is triggered as marginally cost-effective, the treatment previously selected for that section is removed and it is then replaced by the alternate treatment. An example of this process is presented in Figure 18. The duplicate column is used to check whether or not the section had a prior treatment recommendation.

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 17. Benefit-Cost Ratio, Incremental Cost, and Incremental Benefit

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 18. Corrected MCE and Cumulative Cost

The pilot implementation of the preventive maintenance treatment selection tool recommended mainly two treatments: chip seal and THMACO. A review of the developed models showed that these two treatments have the slowest expected rate of pavement deterioration when compared to slurry seal and microsurfacing. However, there were also considerably fewer data points for chip seal and THMACO than for slurry seal and microsurfacing. The limited sample of pavements that received chip seal and THMACO treatments responded relatively well to them. The slurry seal and microsurfacing treatments had a much larger dataset, and there was a high level of variability within the data. Therefore, a comprehensive data review is recommended to be carried out at the district level before final implementation of the proposed methodology.

Figures 19 and 20 compare the results of the developed decision-support tool to the results of the network-level unconstrained analysis as developed in the PMS. Figure 19 shows fewer miles were recommended by the district decision tool than were recommended by VDOT's PMS even though Figure 20 suggests similar levels of spending.

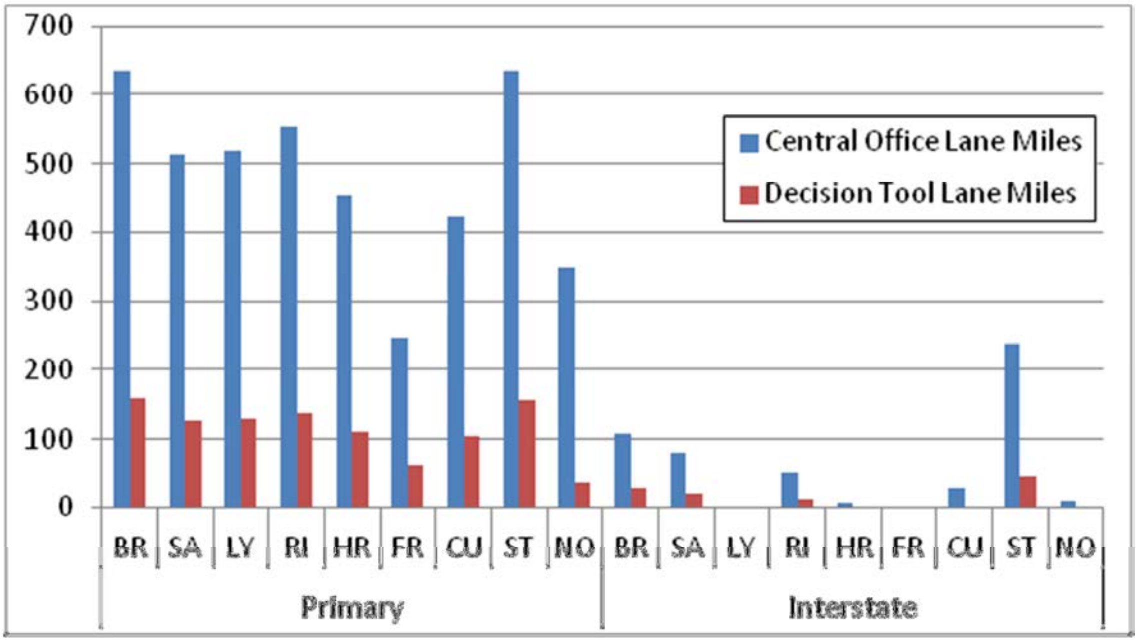

Figure 19. Target Lane-Miles and Recommended Lane-Miles by District and Pavement Classification

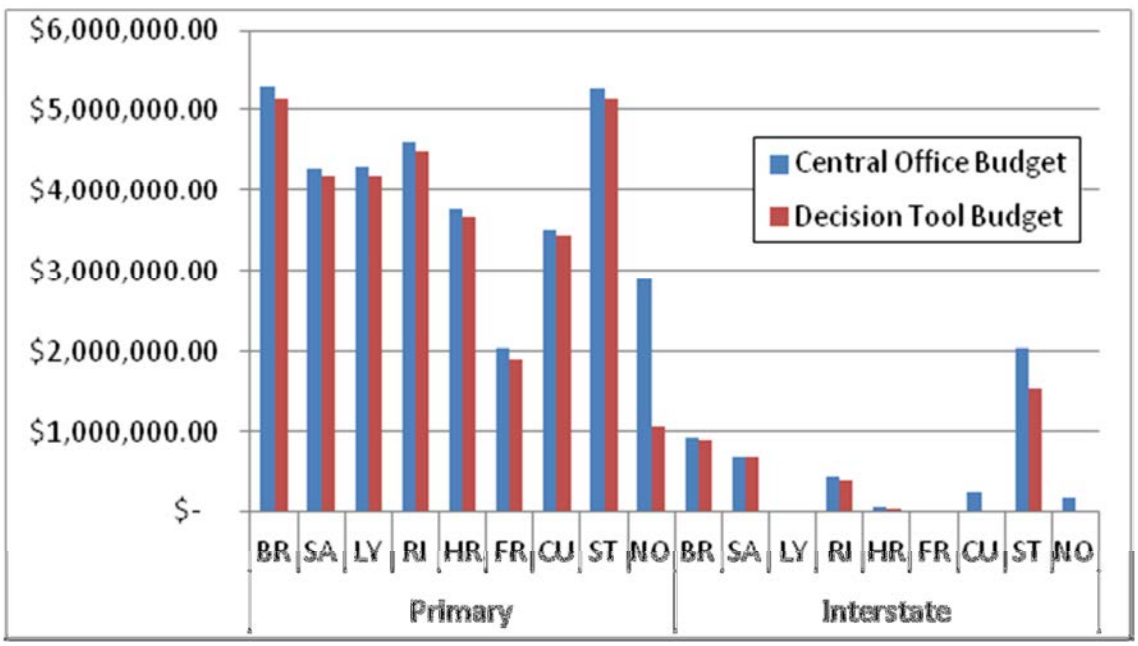

Figure 20. Target Budget and Recommended Budget by District and Pavement Classification

The difference observed is thought to be due to a difference in the treatment cost used. The costs used in the treatment-selection tool are the costs of the specific treatments selected, which may be chip seal, slurry seal, microsurfacing, or THMACO. The expected cost per lane-mile of the preventive maintenance category is computed at the Central Office 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 crack sealing and patching, which heavily influence unit costs developed by the Central Office. As a result, the weighted estimate of preventive maintenance cost developed by the Central Office does not reflect the cost of surface applications as defined in the developed tool.

A comparison of the calculated treatment costs for each pavement section in the analysis to the expected cost for each treatment based on the PMS computations showed that the cost for the preventive maintenance category used in the PMS is 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 default cost for the preventive maintenance category. Based on the performance predicted based on the very limited data available, in most cases, THMACO yielded the highest benefit, so THMACO was 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 analysis lane-miles could be 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 7 through 10.

$$\text{Max } z = \sum x_i b_i / c_i \qquad \text{(Eq. 7)}$$

Subject to

$$\sum x_i c_i \leq p \qquad \text{(Eq. 8)}$$

$$\sum x_i l_i \leq q \qquad \text{(Eq. 9)}$$

$$x_i = 1 \text{ if section i is selected; 0 otherwise} \qquad \text{(Eq. 10)}$$

where

b_i = benefit of section i
c_i = cost of section i
p = recommended budget for PM
q = recommended lane-miles for PM.

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 Figures 21 and 22. The figures show that the total cost of PM treatments and the respective lane-mile recommendations developed using the simpler heuristic (MCE method) were marginally lower than the results obtained from the true optimization. In many cases, instead of selecting one section with a high effectiveness/cost ratio, the optimization method selects multiple sections, each having a slightly lower effectiveness/cost ratio. The sum of the effectiveness/cost for the multiple-section-selection exceeds the cost-effectiveness/cost ratio of the single section. The true optimization method can, therefore, exhaust more of the budget by selecting sections that may have a lower priority because of their effectiveness/cost ratio.

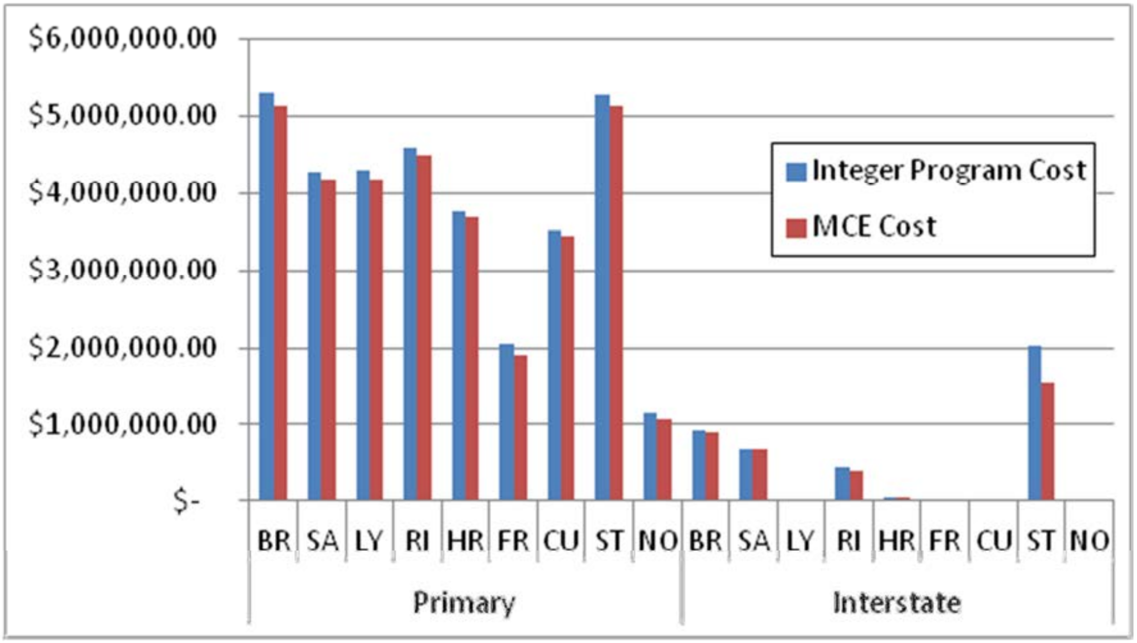

Figure 21. Cost for Integer Program and MCE Computations by District and Pavement Classification

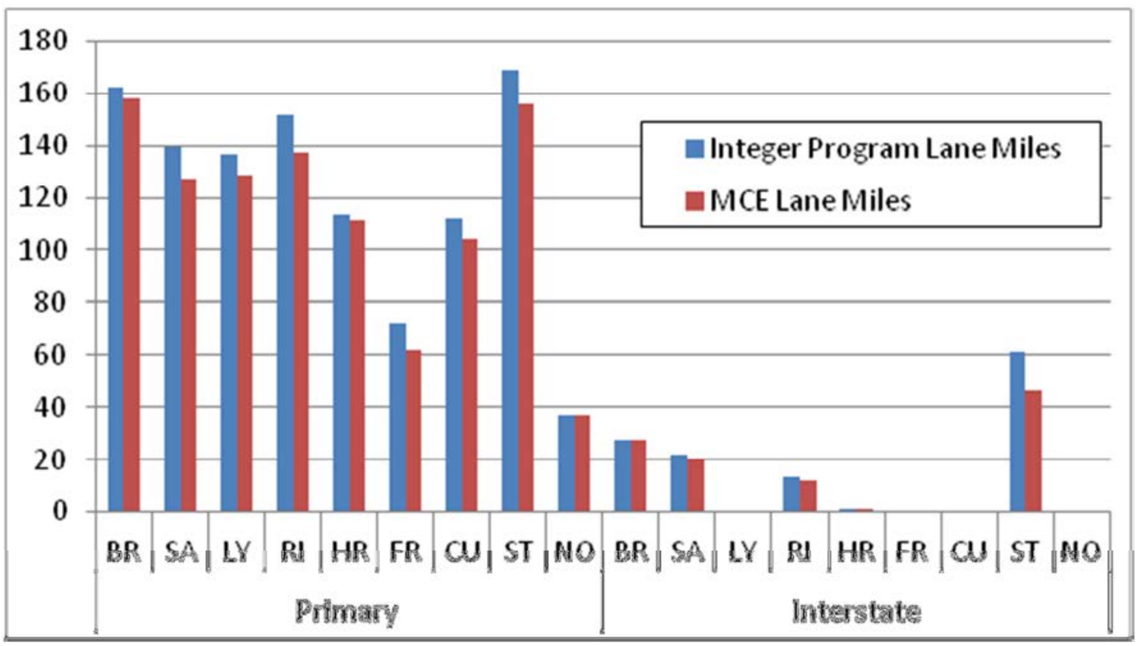

Figure 22. Lane-Miles for Integer Program and MCE Computations by District and Pavement Classification

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 limit 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.

The treatment selection tool outlined in this section is a useful decision support tool that can be immediately implemented in the Virginia maintenance districts. As part of this project, a quick reference guide was prepared for use at the district level to facilitate the execution of the list of pavements that satisfy VDOT requirements for application of preventive maintenance from the PMS. District personnel can use the tool to identify feasible preventive maintenance treatments for each section included in the PMS list that satisfy VDOT requirements for application of preventive maintenance. 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 developed tool can then be improved by updating the expected treatment performance specific to each district.

SUMMARY AND DISCUSSION

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 or a road network.

This project reviewed current and recommended practices for selecting pavement preservation projects and developed a district-level treatment selection tool designed to facilitate the district-level decision-making process. The tool (1) identifies treatment feasibility for each pavement section; (2) assigns the most cost-effective feasible treatment to each pavement section; (3) generates a prioritized list of pavement sections; and (4) selects the projects that maximizes the effectiveness/cost of the selected treatments subject to budgetary and lane-mile constraints set by the Central Office.

The review of current practice and available data showed the following:

- VDOT uses its PMS to perform network analysis to determine maintenance targets for each district, including maintenance type, lane-miles to be maintained, and budget for each maintenance type. The districts then use these recommendations to select the pavements that will receive maintenance and the types of treatments that will be applied to each pavement section.

- VDOT 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 it does not suggest specific treatments to be applied to pavement sections.

- A comparison of the practices in three districts showed that they used different criteria to decide which pavements received preventive maintenance and which preventive maintenance treatments were applied.

- Preventive maintenance treatments currently being used within Virginia include chip seal, slurry seal, microsurfacing, and THMACO. Historical pavement condition data were obtained from VDOT's 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.

- In the initial and revised development of the treatment performance models, it was found that THMACO had the highest expected performance of the four treatments. This treatment had an exceptionally high level of performance; however, this unusually high performance may be at least partially attributed to the small sample size of this dataset. It is believed that this model, when revisited over time, would become more reasonable and show a faster deterioration rate.

A pilot application of the district-level preventive maintenance project selection tool suggested the following:

- 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 created a bias in favor of selection of THMACO and chip seal.

- The heuristic used for selection of the project produced similar results to a "true-optimization" during the limited verification trials.

CONCLUSIONS

- *This project presents recommendations for implementation of a preventive maintenance policy based on best-practice guidelines that can be used by VDOT maintenance districts.* Data from VDOT's PMS were 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 pavement preventive maintenance treatment selection tool, which can be used by the district maintenance personnel for optimizing treatment selection.* This tool determines the near-optimal treatment selection for each pavement maintenance section and provides a prioritized list of pavements to receive these treatments.

RECOMMENDATIONS

Implementation Recommendations

1. *VDOT's Maintenance Division should continue to avoid a "worst first" approach.* When feasible, preventive maintenance should be used to complement major rehabilitation and establish a balance: fix the roads that are in dire need of repair while preventing good roads from deteriorating to that point.

2. *VDOT's maintenance districts, with support from VDOT's Maintenance Division, should start using the district-level pavement preservation treatment selection tool to support the preventive maintenance resource allocation process.* A pilot implementation in two or three districts could help fine tune the tools and develop additional implementation guidance. The use of a common tool will also help develop more consistent criteria for determining treatment feasibility across Virginia. The most recent district-specific cost and performance data should be used to enhance the cost and effectiveness estimations.

3. *VDOT Materials Division should work with VDOT's Maintenance District and the Virginia Center for Transportation Innovation and Research (VCTIR) to develop a "pocket guide" that is modeled after the treatment selection tool for use at the district level.* Although a paper pocket guide is an appropriate first step, developers should consider the functional advantages of a Smartphone app that would supply the same service. The app tool would also facilitate the distribution of guide updates.

Recommendations for Future Research

Although the model was proven practical by the pilot implementation, there are several possible improvements. These include (1) implementing 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; and (2) incorporating continuity constraints (grouping of projects) in project-level selection for construction considerations.

BENEFITS AND IMPLEMENTATION

Benefits

The review of the literature showed that there are significant tangible benefits of integrating an effective preventive maintenance program into the pavement / asset management toolkit. The benefits of keeping the good roads in good condition by applying "low-cost" preventive treatments frequently to extend the life of the pavements can be significant. However, not all VDOT districts are taking full advantage of a pavement preventive maintenance strategy. The implementation of the approaches and tools developed as part of this study can help accelerate the adoption of consistent statewide pavement preservations policies. This will help provide a better service to the traveling public by helping the pavement managers make the best use of the available pavement maintenance resources.

Implementation

The development of the district-level pavement preservation treatment selection tool as a simple Excel spreadsheet should facilitate its adoption, as spreadsheets are routinely used by the district personnel. A pilot implementation effort in two or three districts is anticipated for fall 2015, followed by focused and effective statewide training and full deployment in spring 2016. Training and any ongoing support will be administered through the Pavement Management Office of the Central Office Maintenance Division.

Development of the pocket guide, which will involve engineers from VDOT's Maintenance Division, VDOT's Materials Division, and VCTIR will commence immediately. A draft paper guide is anticipated by late summer 2015. Further development (i.e., Smartphone app development) is anticipated should adoption and use of the paper guide suggest. VDOT's Central Office Maintenance Division will make that determination and work with other divisions (e.g., Materials, VCTIR, IT Applications) as/if required.

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APPENDIX

LITERATURE REVIEW

Background

Preventive maintenance, which is the focus of this report, 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)" (Peshkin and Hoerner, 2005).

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. Furthermore, if pavement distresses are related to structural deficiencies within the pavement, preventive maintenance should not be applied (Johnson, 2000).

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 (Wade et al., 2001).

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 poor-condition pavements while preventing pavements in good condition from deteriorating to the point where preventive maintenance treatments are no longer effective (AASHTO, 2001).

Preventive maintenance has numerous potential benefits, including improved user satisfaction, significant savings in cost, extension of life, and increased safety. 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 (Johnson, 2000).

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 (Peshkin, et al., 2011). An illustration of the two types of crack seal application, flush and overband, is shown in Figure A-1.

Crack seals can be applied to structural cracks. Although it provides no structural benefit, it keeps moisture out of the pavement, slowing 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 (Peshkin et al., 2011).

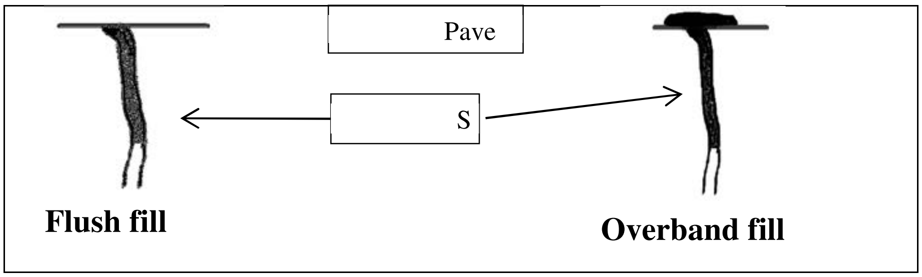

Figure A-1. Crack Seal

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 (Peshkin et al., 2011).

Chip Seals

Chip seals are commonly referred to as surface treatments and are used to improve friction and seal pavements that have non-load-related cracking (Wade et al., 2001). A chip seal may be defined as a sprayed application of asphalt followed by the application of aggregate chips that 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 (Peshkin et al., 2011). An illustration of a chip seal is shown in Figure A-2.

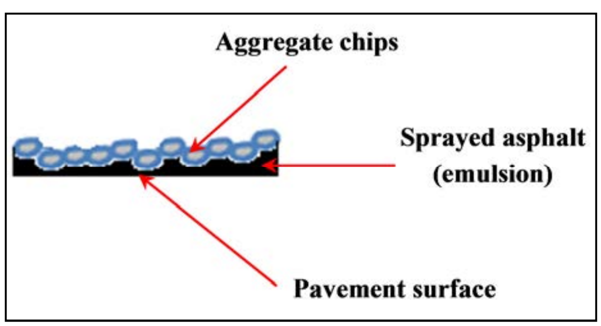

Figure A-2. Chip Seal

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 (>5,000 vpd) or urban roads

(>10,000 vpd) (Peshkin et al., 2011). Curing typically takes 2 hours, after which normal traffic speeds may resume (Peshkin et al., 2011).

Chip seals used on high-volume roadways can result in excess dust, roughness, and noise, and loose chips could potentially damage vehicles. 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, spraying a 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 (Wade et al., 2001).

Slurry Seals

A slurry seal may be defined as a mixture of well-graded fine aggregate and asphalt emulsion (Wade et al., 2001). This mixture is spread over the surface of the pavement with a spreader box fitted to the back of the truck (Peshkin et al., 2011). An illustration of a slurry seal application is shown in Figure A-3.

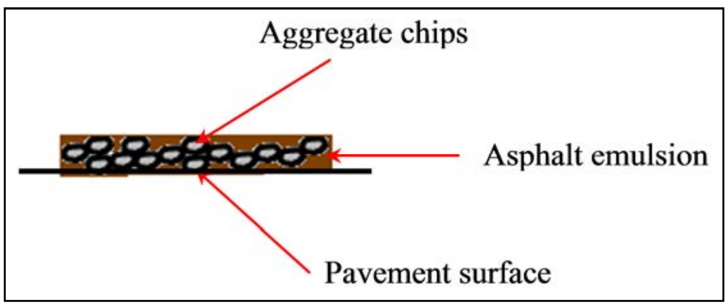

Figure A-3. Slurry Seal

Pavement condition is an important consideration when placing the slurry seal. It may be used to address certain functional distresses, but slurry seals should not be placed on pavements with structural deficiencies because they do not add structural capacity (Peshkin et al., 2011). If there are any areas of localized distress, these should be repaired prior to application of the slurry seal (Wade et al., 2001).

Climate is also an important consideration for a slurry seal because 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, then it is recommended that another treatment be used (Peshkin et al., 2011).

Slurry seals should be placed when the pavement's condition index falls within the range of 70 to 85 and the pavement is 5 to 8 years old. It is provisionally recommended to be used on high- traffic Average Daily Traffic (ADT) rural roads (>5,000 vpd) or urban roads (>10,000 vpd) (Peshkin et al., 2011).

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 (Peshkin et al., 2011). Microsurfacing is similar to a slurry seal; however, the binder is polymer-modified and there are higher quality aggregates (Wade et al., 2001). Microsurfacing can be placed in a single or double application. The double application involves a rut-filling application followed by a full-surface application (Peshkin, et al., 2011).

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 5 to 8 years old. It is generally recommended to be used on high-traffic ADT rural roads (>5,000 vpd) or urban roads (>10,000 vpd) (Peshkin et al., 2011).

Microsurfacing is widely accepted for use on high-traffic-volume roadways (Wade et al., 2001). There is minimal disruption to traffic because curing typically takes 1 hour, after which traffic may resume (Peshkin et al., 2011).

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 because it forms a protective layer over it that improves the binding of the aggregate chips (Peshkin et al., 2011).

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 (Peshkin et al., 2011). A gap-graded aggregate consists of coarse grades and fine grades of aggregate without any medium grades, hence the "gap" in the grading (Wade et al., 2001). An illustration, adapted from Wade et al. (2001), of a gap-graded aggregate is shown in Figure A-4a.

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 5 to 10 years old. It is generally recommended to be used on high-traffic ADT rural roads (>5,000 vpd) or urban roads (>10,000 vpd). It is highly recommended for overnight or single-shift work zone durations (Peshkin et al., 2011).

Thin Hot Mix Asphalt Concrete Overlays (THMACO) and Ultra-Thin HMACO

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 (Wade et al., 2001). Open-graded aggregates predominantly consist of aggregates of the same size, as shown in Figure A-4b. Dense-graded aggregates are well graded, and the aggregate sizes are uniformly distributed (see Figure A-4c). Milling is recommended when surface distresses are evident (Peshkin et al., 2011).

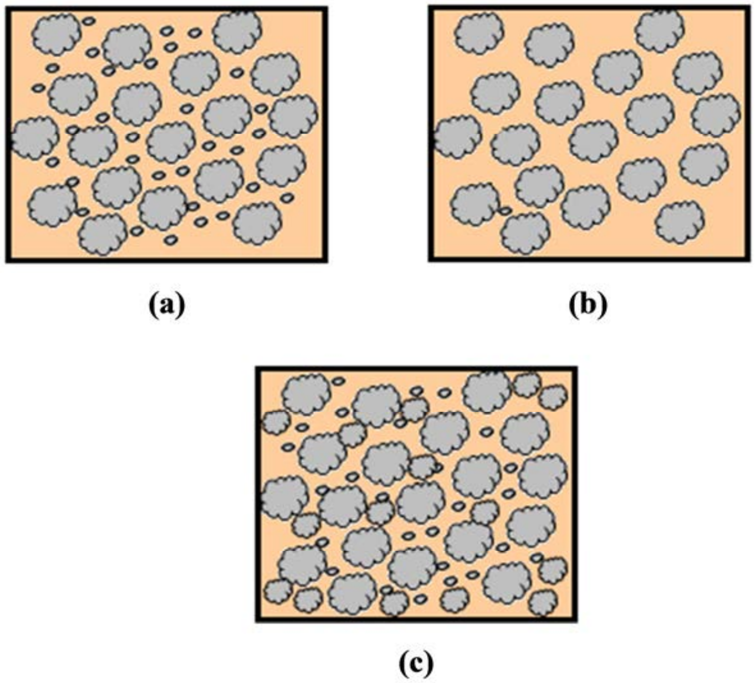

Figure A-4. Illustration of (a) Gap-Graded Aggregate, (b) Open-Graded Aggregate, and (c) Dense-Graded Aggregate (after Peshkin and Hoerner, 2005)

A THMACO should be placed when the pavement's condition index falls within the range of 60 to 80 and the pavement is 6 to 12 years old. It is highly recommended to be used on high-traffic ADT rural roads (>5,000 vpd) or urban roads (>10,000 vpd). It is highly recommended for overnight or single-shift work zone durations (Peshkin et al., 2011).

An ultra-thin THMACO should be placed when the pavement's condition index falls within the range of 65 to 85 and the pavement is 5 to 10 years old. It is generally recommended to be used on high-traffic ADT urban roads (>10,000 vpd). It is highly recommended for overnight or single-shift work zone durations (Peshkin et al., 2011).

Feasibility of Preventive Maintenance Treatments

Tables A-1 and A-2 show the appropriate preventive maintenance treatments for each type of pavement distress according to Johnson (2000). Table A-1 shows preventive maintenance treatment feasibility for each type of surface cracking, while Table A-2 shows the preventive maintenance treatment feasibility for addressing area-wide pavement distresses. Another decision matrix developed by Hicks et al. (1997) is shown in Table A-3. Table A-4 shows the predominant preventive maintenance treatments for each type of pavement distress from a Strategic Highway Research Program (SHRP) report (Peshkin et al., 2011).

Table A-1. Feasible Treatments for Cracks (Johnson, 2000)

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 A-2. Feasible Treatments for Surface Distresses (Johnson, 2000)

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 A-3. Feasible Treatments for Distresses (Hicks et al., 1997)

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

Table A-4. Treatment Feasibility Matrix for Cracking Distresses (after Peshkin et al., 2011)

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. (2011), the expected treatment life, life extension, and unit costs of preventive maintenance treatments are summarized in Table 5A. 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 5A .Expected Performance and Cost of Preventive Maintenance Treatments (Peshkin et al., 2011)

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

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 (Peshkin et al., 2011).

Traffic level affects treatment selection in two ways. First, traffic levels measure the load carried by a roadway, which affect present pavement condition and expected treatment performance. Second, 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 whose failure may have adverse consequences (Peshkin et al., 2011).

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 (Peshkin et al., 2011).

Climate affects treatment selection in two ways. First, climate can affect the expected performance of a treatment. Second, 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, so this treatment should not be applied in cold weather because roadways would have to be closed to traffic for a relatively long time (Peshkin et al., 2011).

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, minimizing the negative effects of lane closures (Peshkin et al., 2011).

Application Timing of Preventive Maintenance Treatments

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 for determining the optimal timing of preventive maintenance (Peshkin et al., 2004).

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 (Peshkin et al., 2004).

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 because 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 because 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. 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 lives of the do-nothing case and the post-treatment case are both computed 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 (Peshkin et al., 2004). The methodology outlined in this study was integrated into a macro-enhanced Microsoft Excel spreadsheet called "OPTime," which is available through the NCHRP website (NCHRP, 2013).

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 an 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 (Peshkin et al., 2004).

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 (Peshkin et al., 2004).

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 (Agile Assets, 2012). 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 (Agile Assets, 2012).

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 (Arambula et al., 2011). Effective performance models can allow realistic predictions of future network condition and also evaluate the effectiveness of maintenance treatments (Chan et al., 1997).

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 because trucks travelling on significantly rough pavements can be excited, 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 smoothing effect on pavements, 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 (Chatti and Lee, 2001).

Preventive Maintenance Treatment Selection Methodologies

Many methods 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 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 (Flintsch and McGhee, 2009). As previously mentioned, factors influencing the selection of preventive maintenance treatments include type and severity of distresses, cost-effectiveness of treatment, climate, and so on (Peshkin et al., 2011).

Decision trees and decision matrices can be used for treatment selection because they can take multiple criteria into consideration. They are usually developed based on 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 (Hicks et al., 1999).

Hicks et al. (1997) 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 (Hicks et al., 1997).

The Maryland State Highway Administration (SHA) (DeSousa, 2011) 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 on 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 (DeSousa, 2011). One of the decision trees used by Maryland SHA is shown in Figure A-5. Each terminal node of the decision tree directs the user to a unique decision matrix.

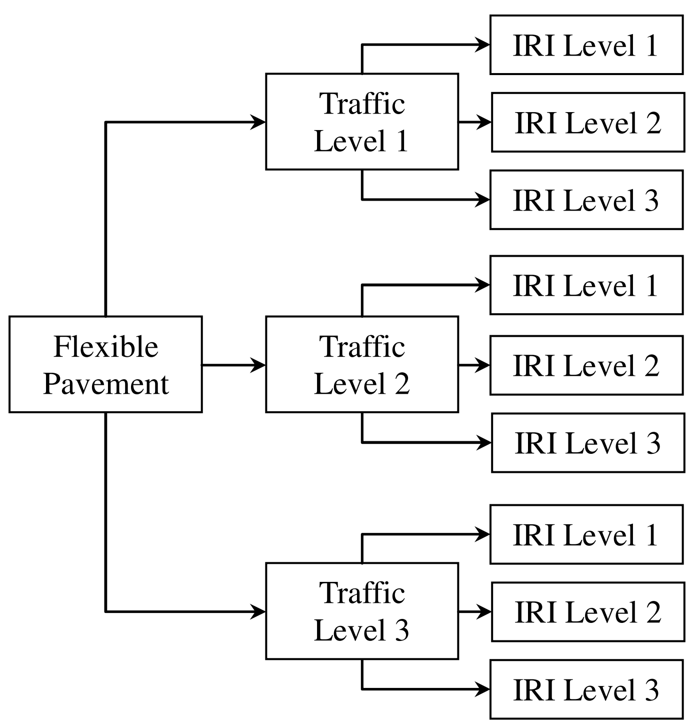

Figure A-5. MDSHA Flexible Pavement Decision Tree (after DeSousa, 2011)

Scoring Systems

In the methodology outlined by Hicks et al. (1999), 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 (Hicks et al., 1999).

A new approach to maintenance selection was developed in Egypt using the maintenance unit (MU). Instead of choosing maintenance and rehabilitation 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 (e.g., reconstruction). It was found that this method is useful when developing a 5-year maintenance plan because it is quite accurate in developing maintenance needs (Abo-Hashema and Sharaf, 2009).

Optimization

Optimization methods perform budget allocation to obtain the combination of selected pavement sections based on their benefit. Limitations on 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 (AASHTO, 2001). Optimization selects the most optimal solution based on maximization objectives such as pavement condition subject to budgetary constraints, or based on minimization objectives such as cost subject to condition constraints. Most optimization is implemented to maximize cost-effectiveness at the network-selection level (Dessouky et al., 2011).

According to Hicks et al. (1997), 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 factors such as cost, expected performance, availability of contractors, environmental impact, availability of materials, and climate. 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 that considers all factors including treatment timing, expected life, and even user delay costs.

According to Wu et al. (2008), 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 the 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. The authors presented a decision-support model that optimizes 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 (Wu et al., 2008).

An alternative to optimization methods would be the use of heuristics, which can provide "near optimal" solutions (AASHTO, 2001). The heuristic approach calculates the marginal cost-effectiveness (MCE) or the incremental benefit-cost (IBC) and is used by numerous highway agencies (Dessouky et al., 2011).

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 A-1 (Dessouky et al., 2011):

$$\mathrm{MCE_i} = \frac{\mathrm{E_i} - \mathrm{E_s}}{\mathrm{C_i} - \mathrm{C_s}} \qquad \text{(Eq. A-1)}$$

where E_i and C_i are the effectiveness and cost of project i, and E_s and C_s are the effectiveness and cost of the selected project (Dessouky et al., 2011).

The IBC approach computes IBC for each project and the previous project. The IBC is calculated as shown in Equation A-2 (Dessouky et al., 2011):

$$\mathrm{IBC_i} = \frac{\mathrm{B_i} - \mathrm{B_{i-1}}}{\mathrm{C_i} - \mathrm{C_{i-1}}} \qquad \text{(Eq. A-2)}$$

where B_i and C_i are the benefit and cost of project i. The highest IBC is selected as the current project, and subsequent projects are compared to the selected IBC (Dessouky et al., 2011).

An example of state implementation of a decision support model is the prioritization methodology, which is used in Texas. The previously available needs assessment tool in the TXDOT Pavement Management and Information System (PMIS) used a decision tree to develop a list of projects that are candidates for preventive maintenance or rehabilitation. A prioritization tool was developed to help 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 weighting 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 (Dessouky et al., 2011).

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