MoDOT Pavement Preservation Research Program
Volume I, Summary Report

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16. Abstract

The following report documents a research project on pavement preservation performed by the Missouri University of Science and Technology (Missouri S&T) and the University of Missouri-Columbia (UMC) on behalf of the Missouri Department of Transportation (MoDOT). The report is in seven separate volumes consisting of a Summary Report followed by six detailed technical reports. To achieve the goal of reducing maintenance costs and improving minor road ratings, MoDOT has embarked upon a plan of formalizing its maintenance/preservation planning. To assist in developing the plan, MoDOT contracted with Missouri S&T and UMC to conduct a research project, entitled "*MoDOT Pavement Preservation Research Program*." The product of this research would become a part of MoDOT's overall Pavement Management System (PMS). The overall objective of the research was to provide a *process* that would allow MoDOT to do more selective planning, better engineering and more effective maintenance to minimize costs while maintaining adequate safety and performance of Missouri's pavements. Six Guidance Documents were created which will act as guidelines for MoDOT's Pavement Specialists and Pavement Engineers. The work was divided into six tasks, each with its own research (Task) team. The focus of the research was on preservation strategies applied to minor routes.

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MoDOT PAVEMENT PRESERVATION RESEARCH PROGRAM
MoDOT Project TRyy1141

FINAL REPORT

VOLUME I
SUMMARY REPORT

August 27, 2015

Prepared for the

Missouri Department of Transportation

by

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EXECUTIVE SUMMARY

The following report documents a research project on pavement preservation performed by the Missouri University of Science and Technology (Missouri S&T) and the University of Missouri-Columbia (UMC) on behalf of the Missouri Department of Transportation (MoDOT). The report consists of a Summary Report followed by six detailed technical reports. To achieve the goal of reducing maintenance costs and improving minor road ratings, MoDOT has embarked upon a plan of formalizing its maintenance/preservation planning. To assist in developing the plan, MoDOT contracted with Missouri S&T and UMC to conduct a research project, entitled "*MoDOT Pavement Preservation Research Program*"**.** The product of this research would become a part of MoDOT's overall Pavement Management System (PMS). The overall objective of the research was to provide a *process* that would allow MoDOT to do more selective planning, better engineering and more effective maintenance to minimize costs while maintaining adequate safety and performance of Missouri's pavements. Six Guidance Documents were created which will act as guidelines for MoDOT's Pavement Specialists and Pavement Engineers. The work was divided into six tasks, each with its own research (Task) team. The focus of the research was on preservation strategies applied to minor routes.

Task 1: The research reported in the Task 1 document (Volume II) was performed by researchers from Missouri S&T and UMC. The objective of Task 1: *Data Collection for Pavement Management: Historical Data Mining and Production of Data* was to develop data for use in MoDOT's pavement preservation program based primarily on historical information available throughout MoDOT, as well as climate data from the National Oceanic and Atmospheric Administration (NOAA) and AASHTOWare (AASHTO), and subgrade soils data from US Department of Agriculture (USDA) and the Arizona State University (ASU) websites. The purpose of Task 1 was to develop a framework for data collection and management that can subsequently be implemented by MoDOT in the future across the state as it fully develops its pavement management system. Data integration from divisions within MoDOT (Planning, Construction and Materials, and Maintenance) will be necessary for a complete system. A pilot database, based on minor routes in the Central District for Full-Depth Asphalt pavements and in six districts for Concrete and Composite pavements, was developed to demonstrate the methodology for future use by MoDOT and for initial use by investigators in Tasks 2 through 6. Numerous databases maintained by MoDOT residing in the above three divisions as well as climate and soils data from other sources were located, collected, supplemented, cleansed, verified, and summarized. Recommendations for changes to MoDOT's present data collection procedures and repositories were developed. Appendix B in Volume II includes the Guidance Document for data retrieval and Appendix C is the Guidance Document for creating or updating models.

Task 2: The research reported in the Task 2 document (Volume III) was performed by researchers from Missouri S&T. Pavement performance models describe the deterioration behavior of pavements. They are essential in a pavement management system if the goal is to make more objective, reliable, and cost-effective decisions regarding the timing and nature of pavement maintenance activities. The general objective of Task 2: *Development of Pavement Family and Treatment Performance Models* was to develop performance models for a variety of pavement families and pavement preservation treatments used by MoDOT. Ideally, all MoDOT routes will eventually be divided into homogeneous sections. Each roadway section will have its own condition plots for International Roughness Index (IRI) and PASER rating deterioration. The fitted curves can be extended to the action threshold of choice; for example, one commonly used threshold is where reconstruction is the only option. Sometimes, however, there will not be sufficient data to plot a site-specific curve, especially in the early going of setting up this part of a Pavement Management System. A family model can be used as a surrogate for the site-specific curve. The family curve is one fitted to many other similar sections.

Using the data collected in Task 1, linear least-squares regression techniques were used to generate deterministic models that predict the International Roughness Index (IRI), the pavement condition measure most widely in use today. There was insufficient data available for the recently-adopted PASER overall condition index to develop models. Family IRI-prediction models were developed for full-depth asphalt (FDA), concrete (PCC), and composite (Comp) pavements. Treatment IRI-prediction models were developed for 1-in. overlays on FDA pavements, chip seals on FDA pavements, and 3¾-in. overlays on PCC pavement.

Predictor variables consistently shown to be highly significant in predicting IRI for both FDA asphalt and Comp pavements were initial IRI (IRI_o which is the IRI value right after treatment) and pavement surface age (SA). The majority of the PCC pavement sections selected were so old that IRI_o could not be determined (or estimated with any confidence), therefore SA was the dominant predictor variable in the PCC pavement family model. Terminal IRI (IRI_t which was the IRI just prior to a treatment) was also a significant predictor of IRI and was directly or indirectly included in the FDA and Comp family and treatment models. Additional significant IRI predictors (depending on the model) were the climate parameters DT32 (days/year that air temperature was below freezing), FT (freeze/thaw cycles per year), and DP01 (days/year that precipitation was at least 0.1-in.), subgrade soil parameters P200 (percent passing the #200 sieve) and Pclay (percent clay-size soil), and LstTrtThk (the last treatment thickness).

Although the literature indicated that traffic is a significant factor affecting treatment service life, neither Annual Average Daily Traffic (AADT) nor Annual Average Daily Truck Traffic (AADTT), both measured by direction of travel (one-way), showed significance as predictors on their own. Even accumulated traffic, the product of SA and AADT (or AADTT), seldom showed significance and/or possessed the expected sign on the regression coefficient. The theory is that a compounding of inaccuracies occurs in the traffic data due to a series of assumptions by MoDOT in the assignment of traffic volume to pavement sections, and possibly subsequent decisions by the Task 1 researchers regarding traffic volume fluctuation over time. Another reason that could explain why increasing traffic did not show up significantly in the models as a cause for increasing IRI could be that some variables that reduce deterioration rates are associated with traffic level and actually increase along with increasing traffic: thickness, quality of materials and construction, and maintenance quality; an increase in these variables will counteract to a certain degree the deteriorating action of increasing traffic.

Task 3: The research reported in the Task 3 document (Volume IV) was performed by researchers from Missouri S&T and UMC. The overall goal of Task 3: *Pavement Evaluation Tools – Data Collection Methods* was to conduct a literature search to identify and evaluate methods to rapidly obtain network-level and project-level information relevant to in situ pavement condition to enable pavement maintenance decisions. The focus of these efforts was to explore existing and new technologies that can be used to collect data and develop the knowledge, procedures, and techniques that will allow MoDOT to perform pavement evaluation. It was concluded that each of the recommended technologies could be utilized effectively by appropriately trained MoDOT personnel. The ultrasonic surface wave, impact echo, ground penetrating radar and electrical resistivity tools are readily stored and can be transported to a work site in a pick-up truck. The falling weight deflectometer and rolling dynamic deflectometer require dedicated vehicles. The field data acquired using all eight technologies are readily processed using commercially-available software and a laptop or desktop computer. Only two of the eight recommended technologies (ground-coupled ground penetrating radar (GPR) and air-launched GPR are compatible with the ARAN vehicle. Only air-launched GPR was recommended for network evaluation. Application of these technologies could ultimately enable pavement maintenance decisions that minimize cost and maintain/improve pavement quality.

The Volume IV report presents a tabular summary of methods previously used by MoDOT to evaluate pavement condition, and a summary of methods investigated to evaluate pavement and subsurface conditions.

Task 4: The research reported in the Task 4 document (Volume V) was performed by researchers from Missouri S&T and UMC. The overall objective of Task 4: *Site Specific Pavement Condition Assessment* was to thoroughly assess the cost-effectiveness and utility of selected non-invasive technologies as applicable to MoDOT roadways.

Technologies investigated in this project were Ultrasonic Surface Waves (USW), Impact Echo (IE), Ground-coupled Ground Penetrating Radar (GPR) (400 MHz and 1500 MHz antennae), Electrical Resistivity Tomography (ERT), Multichannel Analyses of Surface Waves (MASW), Falling Weight Deflectometer (FWD), Rolling Dynamic Deflectometer (RDD), and Air-launched Ground Penetrating Radar (GPR). USW, IE, ground coupled GPR (1500 MHz antennae), ERT, MASW, FWD, and RDD were used to acquire non-invasive data along eight project-level roadways, while GPR (400 MHz) and air-launched GPR were used to acquire data along two network-level roadways. Pavement cores extracted from each site served as ground truth for the non-invasive imaging technology results. Results of each investigation are summarized in the main body of the Task 4 report and are summarized by technology. Positive outcomes were realized by six of the seven technologies applied to the project-level roadways. The only technology that did not consistently generate positive outcomes was Impact Echo. Positive outcomes were realized by both technologies applied to network-level investigations. It was concluded that air-launched GPR can be used as the primary application for determination of bituminous layer thickness, debonding, stripping, and void detection. High-frequency ground-coupled GPR can be used as the primary application for bituminous layer thickness, debonding, reinforcing mesh location, and void detection. Low-frequency ground-coupled GPR can be used for location of shallow utilities. Ultrasonic surface wave analysis can be used for bituminous layer thickness determination. Appendix A in Volume V includes the Guidance Document based on the results of the project-level and network-level investigations conducted.

Task 5: The research reported in the Task 5 document (Volume VI) was performed by researchers from Missouri S&T. The general objective of Task 5: *Pavement Treatment Trigger Tables/Decision Trees and Treatment Candidate Selection Process* was to provide a manual that MoDOT can use to select the most appropriate pavement treatment for a given roadway project. The selection procedure includes cost assessment methods. Salient to any pavement management system is the process of determining potential treatment options, and the subsequent selection of the final treatment choice. Task 5 thus entailed the development of pavement treatment trigger tables and the treatment candidate selection process.

Armed with the treatment tables and the selection process, MoDOT will be able to select appropriate treatments by use of treatment matrices showing the most appropriate applications for given specific site conditions and then be able to perform a cost analysis for each candidate treatment. The idea in using a decision table is to decide which optional treatments will be required to keep a given route in a system rating of "Good", move a rating of a given road from "Poor" into "Good", or in an extreme case, from "Poor-Unsafe" to "Poor-Safe". The final selection of the optimum treatment from the possible ones would be done in a network prioritization activity (not part of this research project).

The input to the trigger tables entails such factors as an overall condition indicator (PASER), smoothness (IRI), individual distress types-extent-severity (e.g. thermal cracking, block cracking, fatigue cracking, longitudinal cold joint cracking, joint reflective cracking, longitudinal wheel path cracking, longitudinal edge breakup, patches and potholes, raveling, polishing, stable rutting, corrugations and shoving, bumps and sags, bleeding, D-cracking, pop-outs, spalling, corner cracks, faulting), pavement type, history of treatment, and some measure of traffic through the surrogate Surface Age.

Trigger table output is one or more potential appropriate treatments, which would consider pavement condition, traffic, climate (which affects construction timing and treatment performance), work zone duration (e.g. traffic control issues), time of year construction, construction quality risk, availability of quality contractors and quality materials, longevity of treatment, and availability of funding. Trigger tables include preservation treatments (chip seals, micro-surfacing, slurry seals, ultrathin bonded asphalt wearing surface (UBAWS), crack sealing, crack filling, thin overlays, milling and filling, profile milling, hot in-place recycling, cold in-place recycling, whitetopping, diamond grinding, load transfer retrofit and joint repair, and partial/ full depth repair.

Task 6: The research reported in the Task 6 document (Volume VII) was performed by researchers from UMC. The objective of this Task: *Re-Calibration of Triggers and Performance Models* was to develop the concept and framework for a procedure to routinely re-calibrate and update the Trigger Tables, Family models, and Treatment Impact (Performance) Models as well as create new Segment-specific deterioration curves, new Family models, and additional Treatment Performance models. The scope of work for Task 6 included a limited review of the recent pavement management systems literature for key elements for inclusion, strategies and procedures used to update pavement performance (deterioration) models, and triggers for initiating a treatment evaluation. Because this is a relatively new process, the task entailed contacting and surveying several state DOTs that already have an updating process in place. The task included interaction with MoDOT personnel in order to be sure that the proposed framework for the re-calibration procedure can incorporate what MoDOT already does and is compatible with current practices in MoDOT. The report summarized the need for updating the models developed in Task 2 and used in Task 5. There were three family models: Full-Depth Asphalt, Concrete, and Composite as well as three treatment performance models: 1-in. overlays on asphalt, chip seals on asphalt, and thin structural overlays on concrete.

Recommendations for future enhancements of the required data were presented. The necessity for creation of new models was emphasized: Segment-specific models, new Family models, and additional Treatment Performance models, in terms of both IRI and PASER ratings. Updating the treatment trigger tables (created in Task 5) was also discussed. Finally, a detailed list of obstacles to data mining and handling with possible solutions was offered. To reap full benefit from the overall pavement maintenance program, it will be incumbent upon MoDOT personnel to adapt and implement the re-calibration framework in order to realize the full potential of the modified pavement management process.

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The research for the "*MoDOT Pavement Preservation Research Program*" was performed by Missouri S&T and UMC. The principal investigator and technical advisor for all Tasks was David Richardson. Co-principal investigators were Neil Anderson, Ronaldo Luna, Michael Lusher, and Lesley Sneed from Missouri S&T and Brent Rosenblad, John Bowders, and Andrew Boeckmann from UMC. Task leaders were: Tasks 1, 2, and 5: David Richardson, Task 3: Neil Anderson, Task 4: Lesley Sneed, and Task 6: Brent Rosenblad and John Bowders.

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Finally, the authors also appreciate the tireless staff and students of the Department of Civil, Architectural, and Environmental Engineering and the Department of Geosciences and Geological and Petroleum Engineering at the Missouri S&T and the Department of Civil Engineering at the UMC. Their assistance both inside and out of the various laboratories was invaluable to the successful completion of this project.

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1 INTRODUCTION

1.1 REPORT ORGANIZATION

The following report documents a research project on pavement preservation performed by the Missouri University of Science and Technology (Missouri S&T) and the University of Missouri-Columbia (UMC) on behalf of the Missouri Department of Transportation (MoDOT). The report consists of a Summary Report followed by six detailed technical reports. Chapter 1 of the Summary Report presents the report organization and background for the study. The project work plan is presented in Chapter 2 and includes the overall objectives, scope, and project tasks of the research study. Following the project work plan, the summary findings, conclusions, and recommendations are presented task by task in Chapter 3, with overall summary and recommendations in Chapter 4.

1.2 BACKGROUND

1.2.1 Project Background

At the outset of this study, MoDOT had a goal of achieving two critical and timely operational needs:

- Reduced system-wide pavement maintenance costs
- Maintaining the service rating of major roads (≥ 85% good rating) and improving the rating for minor roads

To achieve the goal of reducing maintenance costs and improving minor road ratings, MoDOT embarked upon a plan of formalizing its maintenance/preservation planning. To assist in developing the plan, MoDOT contracted with Missouri S&T and UMC to conduct a research project, entitled "*MoDOT Pavement Preservation Research Program*"**.** The product of this research would become a part of MoDOT's overall Pavement Management System (PMS).

1.2.2 Pavement Management Systems

A Pavement Management System has been defined as "a set of tools or methods that assist decision-makers in finding optimum strategies for providing, evaluating, and maintaining pavements in serviceable conditions over a period of time". A portion of PMS is the "identification of pavement maintenance, preservation, and rehabilitation recommendations that optimize the use of available funding" (Zimmerman et al. 2011). Fig. 1.1 shows the concept of the change in a given pavement's condition over time, and the optimum time for various interventions.

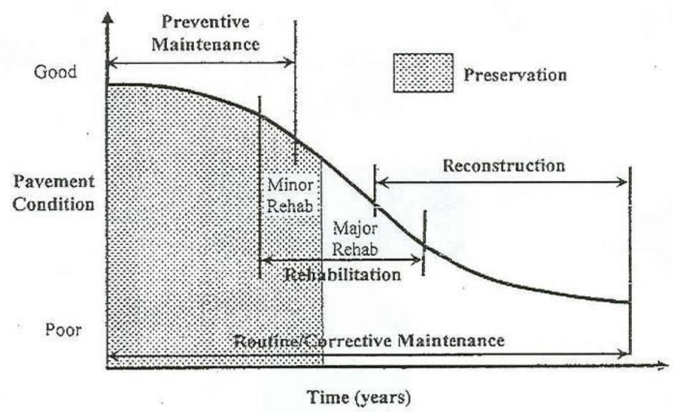

Figure 6-1. Relationship between pavement condition and different categories of pavement treatment (adapted from Peshkin et al. 2007).

Fig. 1.1 – Conceptual plot of pavement condition vs. time (Zimmerman 2011).

"*Pavement Preservation*" involves a set of practices that extends pavement life. The practices include *Preventive Maintenance*, *Minor Rehabilitation*, and *Corrective Maintenance* (Peshkin et al. 2011a). As can be seen from Fig. 1.2, there is some overlap of these practices in regard to definitions. For the purposes of this study, "*Minor rehabilitations"* are *programmed* non-structural enhancements that occur in the early-to-middle years of a pavement's life when serviceability/ride issues become apparent. Examples are thin hot mix asphalt (HMA) and cold mix asphalt (CMA) overlays and mill-and-overlays. MoDOT maintenance forces sometimes call these "Treatments", as discussed in the Task 1 report. *"Preventive Maintenance"* includes *programmed* activities that preserve the system, retard future deterioration, and maintain or improve functional condition without adding significant structural capacity. These strategies are applied early in the deterioration-time curve before significant structural deterioration. MoDOT maintenance forces sometimes call these "Preventive Treatments". Examples presented in MoDOT's Engineering Policy Guide (EPG) are crack sealing/filling, joint sealing, and surface treatments (chip seals, scrub seals, scratch-and-seals, fog seals, onyx seals, spot-seal coating, ultrathin bonded asphalt wearing surface (UBAWS), and micro-surfacing) (MoDOT 2014). *Corrective Maintenance* is *non-programmed* work performed in response to unforeseen development of deficiencies that impact safety/operational deficiencies. MoDOT maintenance forces sometimes call these "Reactive Treatments". An example is partial patching. As can be seen from Fig 1.1, there is some overlap in the timing of these arbitrarily-defined actions and what they are named, especially thin overlays.

Fig. 1.2 shows the concept of comparing different treatment strategies at different intervention times with the subsequent consequences for a given route. The curves represent models; the initial or original curve would be from actual historical data for the specific route, or, if not enough history for that route is available, a Family model (curve) would be substituted. Each of the other curves would be "Treatment Impact (Performance) Models". Traditionally, state DOTs divide Pavement Families into Concrete (perhaps several families, based on design features or traffic volume), asphalt-on-concrete (Composites) [perhaps several families based on thickness or traffic volume], and Asphalt (perhaps several families based on thickness or traffic volume, or presence of granular base, and thickness of base). For example, in the present study, working with minor routes, essentially all composite pavements in the dataset were Jointed Reinforced Concrete Pavements (JRCP) at 61.5 ft length, so there was only one family in this category. Most minor route asphalt pavements did not have a history of construction, thus details of asphalt thickness and presence of significant granular base were not available, so all asphalt pavements were called “Full-Depth Asphalt”.

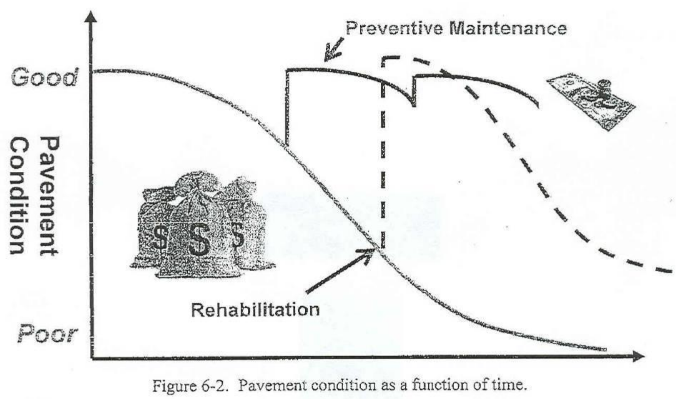

Fig. 1.2 – Conceptual plot of pavement condition vs. time with different interventions (Zimmerman et al. 2011).

The thrust of this research was concentrated on preventive maintenance and preservation as shown in Fig. 1.1.

2 WORK PLAN

2.1 General

As with most research projects, the project work plan evolved during the course of the study as results became available. The work plan described below reflects the work as completed on the project.

2.2 Objective

The overall objective of the research was to provide a *process* that would allow MoDOT to do more selective planning, better engineering and more effective maintenance to minimize costs while maintaining adequate safety and performance of Missouri's pavements. Six Guidance Documents were created which will act as guidelines for MoDOT's Pavement Specialists and Pavement Engineers.

2.3 Scope of Work

2.3.1 Modified Pavement Management Process

The broad spectrum of activities and factors that impact the performance and cost of pavement preservation are shown in the modified pavement management process flow chart (Fig. 2.1).

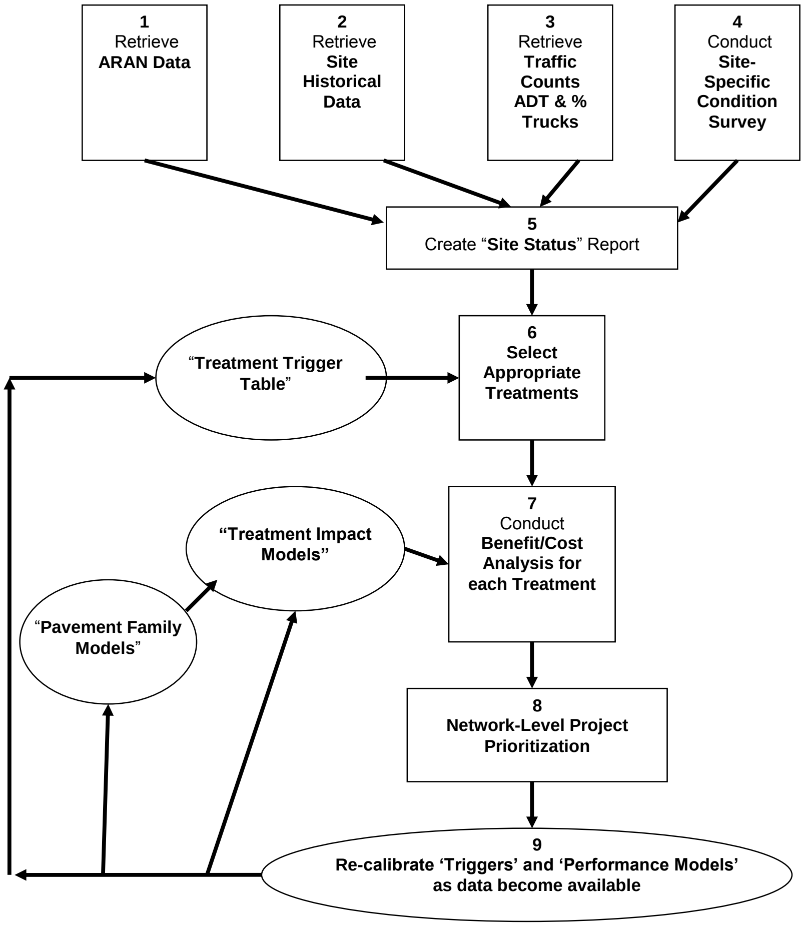

Fig. 2.1 – Procedural steps for implementing a modified pavement management process (Zimmerman et al. 2011).

In general, the pavement treatment selection process within a PMS entails the following steps. This information was taken from the updated *AASHTO Guide to Pavement Management* (Zimmerman et al. 2011) that MoDOT strongly recommended to the project team. Based on the AASHTO Guide, the following is the nine-step procedure that a MoDOT Pavement Specialist or Pavement Engineer would use for implementing the *modified pavement management flowchart* (Fig. 2.1). The procedure would be followed for a given proposed road maintenance/preservation/rehabilitation project. The word "retrieve" is used to emphasize that the data, models, and tables to be used would already exist:

Step 1-Retrieve annual road condition survey (e.g. Automatic Road Analyzer [ARAN]) data

Step 2- Retrieve site historical data: e.g. materials, thicknesses, subgrade soil, drainage, weather, construction records, etc.

Step 3- Retrieve traffic information: Annual Average Daily Traffic (AADT) and percentage trucks, or Annual Average Daily Truck Traffic (AADTT) or Commercial Truck Volume

Step 4- Conduct a site-specific condition survey (visual, coring, non-destructive testing)

Step 5- Combine information from steps 1 through 4 into a "Site Status" report. Identify the roadway as a certain "Pavement Family" type (see Table 2.1 for potential families; the actual families determined in Task 2 are presented later)

Step 6- With "Site Status", enter appropriate "Treatment Trigger Table" and select several alternate treatments (Table 2.2) appropriate for the assigned Family or specific route segment

Step 7- With the appropriate "Treatment Impact (Performance) Models," conduct a cost effectiveness analysis for each potential appropriate treatment (Fig. 2.2)

Step 8- Using the calculated cost effectiveness of all treatments and all projects, conduct a network-level (county, region or state-wide) project prioritization list. Project prioritization could be based on other considerations in addition to cost effectiveness

Step 9- Recalibrate or update Trigger Tables, segment-specific deterioration curves, Family Models, and Treatment Impact (Performance) Models as additional performance monitoring data become available, technologies in assessment or pavement materials change, and agency policies change (this is an on-going step resulting in a sustainable process that leads to the best evidence-based decisions, even as the "evidence" (available data and information) changes over time)

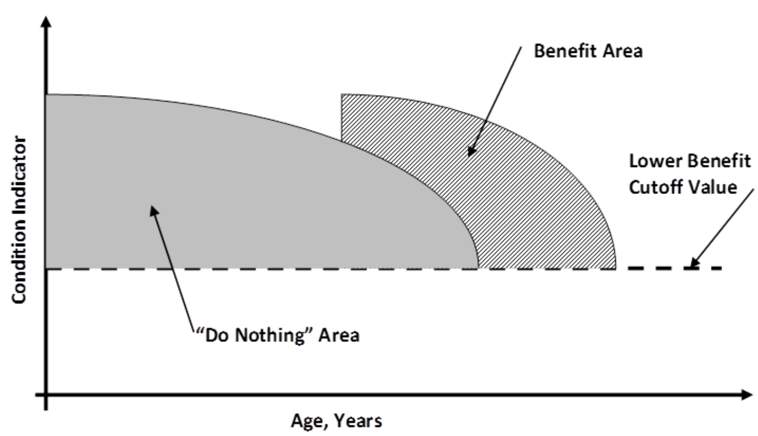

Fig. 2.2 – Illustration of benefit calculation using increased pavement performance (Zimmerman et al. 2011). The cross-hatched area represents the benefit achieved by applying a specific treatment to a pavement.

Table 2.1 – Potential definitions of pavement families in Missouri in a mature PMS*

Flexible:
▪ < 7 in. Full-depth asphalt[1]
▪ ≥7 in. Full-depth asphalt[1]
Composite:
• Asphalt over concrete
• Concrete over asphalt (whitetopping)
Concrete:
▪ JPCP, 15 ft joint spacing
▪ JRCP, 61.5 ft joint spacing
▪ CRCP
▪ Bonded concrete overlay over concrete
▪ Unbonded concrete overlay over concrete

[1] may include nominal unbound granular base

* Tasks 1 and 2 created fewer Families, which are presented later in Volume II

Table 2.2 – Example of pavement treatment types used in Missouri (not limited to MoDOT)*

Pavement Treatment Types
▪ Crack sealing/filling and joint sealing
▪ Chip sealing, fog sealing, scrub sealing, scratch sealing
▪ Micro-surfacing, slurry sealing, onyx slurry sealing
▪ Thin HMA overlays: 1 ¾, 1 ¼ or 1-in.
▪ Ultrathin Bonded Asphalt Wearing Surface (UBAWS)
▪ Scratch and seal
▪ Mill & fill, mill & overlay (see above overlays)
▪ Asphalt Cold In-Place Recycling (CIR)
▪ Asphalt Hot In-place Recycling (HIR)
▪ Diamond grinding
▪ Load transfer retrofit & joint repair
▪ Partial/ full depth repair
▪ Whitetopping

* Structural overlays: 3 ¾, 3 ¼ or 2 ¾-in. thickness would not be considered as preventive treatment, but rather as Minor Rehabilitation; Full Depth Reclamation (FDR) would be considered as Reconstruction

2.3.2 Project Tasks

For this research project, six tasks were identified that were necessary to develop the pavement management process for MoDOT through collaborations with MoDOT personnel. The following pavement preservation program tasks, as shown in Fig. 2.3, provided the necessary efforts of each step in the pavement preservation process. The tasks were mapped to the chapters in the *AASHTO Guide to Pavement Management*.

1. Task 1: Data Collection for Pavement Management: Historical Data Mining and Production of Data
2. Task 2: Development of Pavement Family and Treatment Performance Models
3. Task 3: (Non-Destructive Evaluation) Pavement Evaluation Tools-Data Collection Methods
4. Task 4: Site Specific Condition Assessment
5. Task 5: Pavement Treatment Trigger Tables/Decision Trees and Treatment Candidate Selection Process
6. Task 6: Re-Calibration of Triggers and Performance Models

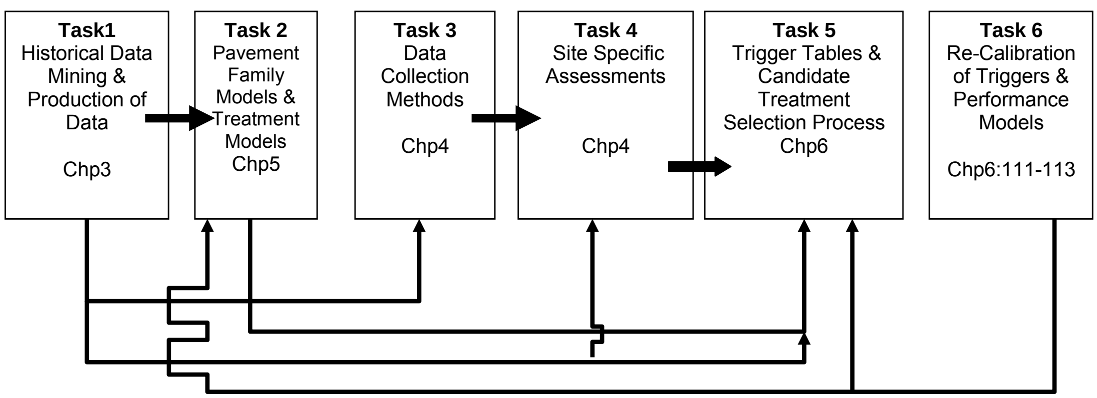

Fig. 2.3 – Tasks in the Pavement Preservation Program and their interactions. Chapter references refer to the pertinent section of Zimmerman et al. (2011).

During the pavement preservation research program, members of the research team interacted with MoDOT personnel to explore the types of data sources that were available. As it turned out, certain kinds of data did not exist or were too difficult for MoDOT to retrieve and supply to the research team; when this necessitated a different approach, the scope of the project necessarily shifted. The following are examples of decisions that were only possible after the contract began and there was interaction that occurred between Missouri S&T/UMC and MoDOT personnel: finalizing the types of pavement families, finalizing types and levels of detail in the trigger tables, types of performance models that were feasible, method of creating and populating the performance models, condition indices that needed to be tracked, kinds of data that needed to be collected by MoDOT in the future, and methods of inventorying data (considering any constraints imposed by MoDOT capabilities).

In the following sections are discussions of each of the individual tasks.

2.4 Task 1: Historical Data Mining and Production of Data

Task 1 involved development of methods of historical data mining and production of data (both MoDOT and non-MoDOT) necessary for the research project, including information on subgrade, traffic, climate, existing pavement structure conditions, and data on the historical performance of all pavement types under all condition types. Secondly, the Task 1 effort involved development of a Guidance Document for the practice of reduction and analysis of historical pavement performance data (Step 2 Fig. 2.1), which should be made available for inclusion in MoDOT's PMS. The purpose of Task 1 was to develop a data collection *methodology* that can subsequently be used by MoDOT pavement treatment planners in the future across the state as MoDOT fully develops its pavement management system. In the *pavement preservation research* program, enough real data was mined to validate the viability of the methodology. Deliverables were: 1) data retrieval methodology "Guidance Document", and 2) sufficient data to develop the models and trigger tables required in Tasks 2 and 5. The deliverables are included in Volume II of the *MoDOT Preservation Research Project* report (Richardson et al. 2015). The sub-tasks are listed below:

1. Sub-task 1A: Conduct literature review
2. Sub-task 1B: Identify and access MoDOT and other data sources
3. Sub-task 1C: Retrieve pavement data for use by the subsequent tasks (Tasks 2 and 5) in this research project
4. Sub-task 1D: Develop a methodology for data management
5. Sub-task 1E: Prepare Guidance Document

2.5 Task 2: Family and Treatment Performance Models

Task 2 involved the examination of all pavement types identified in the MoDOT system for minor routes in the Central District (Full-Depth Asphalt) and in six districts (Concrete/Composite) and the grouping of each into a *Pavement Family Model*. Then, a selection of several prominent pavement treatment types per family model and the development of *Treatment Impact (Performance) Models* (Fig. 2.1) using data produced from Task 1 was done. These pavement deterioration models based on Missouri practices, geological conditions, meteorological conditions, and historical performance evidence were incorporated into Task 5 and used in Step 7 Fig. 2.1. Task 2 documented what other state DOTs have already done and adapted and adopted their treatment impact performance models as appropriate (Ch. 5 Zimmerman et al. 2011). Not every treatment method used by MoDOT had sufficient data to create a particular treatment model. Missing treatments will have to be added as MoDOT accumulates data in the future. Task 2 deliverables were: 1) Pavement Family Models, and 2) several Treatment Impact (Performance) Models per Family Model. The deliverables are included in Volume III of the *MoDOT Preservation Research Project* report (Richardson and Lusher 2015a). The sub-tasks are listed below:

1. Sub-task 2A: Conduct literature review
2. Sub-task 2B: Gain an understanding of MoDOT's experience with performance modeling and its expectations for any newly developed models, create the pavement families, and compile the database into a usable format for model-building
3. Sub-task 2C: Conduct development of pavement performance models and treatment impact models

2.6 Task 3: Pavement Evaluation Tools-Data Collection Methods

Concurrent with other tasks, Task 3 explored the production of currently used and newer kinds of data to be collected either by ARAN during the annual condition survey or by separately-deployed systems, including falling weight deflectometer (FWD), ground penetrating radar (GPR), and others. Task 3 also provided guidance to rapidly obtain broad-area information for use in Step 1 (Fig. 2.1), and collected detailed design parameters and site conditions (in situ section details, soil moisture, and soil/pavement stiffness, among others) for pavements designated for maintenance for use in Task 4 (Fig. 2) and Steps 4, 5 and 6 (Fig. 2.1) (Ch. 4 Zimmerman et al. 2011). Deliverables were comparative summaries of State-of-the-Art methods to collect pavement data (with a focus on non-invasive methods). The deliverables are included in Volume IV of the *MoDOT Preservation Research Project* report (Anderson et al. 2015a). The sub-tasks are listed below:

1. Sub-task 3A: Evaluate NDE methods used by MoDOT
2. Sub-task 3B: Evaluate NDE methods used in the pavement industry
3. Sub-task 3C: Evaluate NDE methods being developed from research
4. Sub-task 3D: Develop comparative benefit-cost analysis
5. Sub-task 3E: Select, procure, and test methods for evaluation in Task 4

2.7 Task 4: Site Specific Condition Assessment

Task 4 involved the development of a manual for site specific condition assessments. The deliverable was a Guidance Document, including a matrix on what site assessment technologies are applicable, how to employ them, and what site condition data can be obtained for use in Steps 1 and 4 (Fig. 2.1). The Guidance Document detailed the types of information desired and the methods (existing or new) to obtain the information. The types of information included were: subgrade characteristics, granular base (thickness, quality), pavement structure, and pavement condition. The deliverables are included in Volume V of the *MoDOT Preservation Research Project* report (Anderson et al. 2015b). The sub-tasks are listed below.

1. Sub-task 4A: Select sites
2. Sub-task 4B: Schedule and acquire data
3. Sub-task 4C: Process data
4. Sub-task 4D: Interpret and analyze data
5. Sub-task 4E: Prepare Guidance Document

2.8 Task 5: Pavement Treatment Trigger Tables/Decision Trees and Treatment Candidate Selection Process

Task 5 involved the creation of Treatment Trigger Tables and a Treatment Candidate Selection Process. A procedure was furnished to select appropriate treatments (design) including a treatment matrix showing the most appropriate applications for given specific site conditions (Step 6 Fig. 2.1) and to perform a cost analysis (Step 7 Fig. 2.1) for each candidate treatment to ultimately recommend a specific treatment. (Ch. 6 and Ch. 7 Zimmerman et al. 2011). The idea in using the table is to decide what optional treatments it will take to preserve the system rating as Good, move the system rating from Poor into Good, or in an extreme case, move from Poor-Unsafe to Poor-Safe. Deliverables are: 1) trigger tables, and 2) cost effectiveness methodology (roadway project-specific). The deliverables are included in Volume VI of the *MoDOT Preservation Research Project* report (Richardson and Lusher 2015b). The sub-tasks are listed below.

1. Sub-task 5A: Procure laboratory equipment and AASHTOWare software
2. Sub-task 5B: Conduct literature search
3. Sub-task 5C: Engage in discussions with MoDOT to obtain information about pavement types, treatment types, selection criteria, mixes, and past history
4. Sub-task 5D: Conduct treatment option analysis using AASHTOWare
5. Sub-task 5E: Conduct mixture testing and analysis
6. Sub-task 5F: Create a manual of treatment trigger tables and cost effectiveness procedures

2.9 Task 6: Re-Calibration of Triggers and Performance Models

Task 6 involved the development of the framework that will guide MoDOT in creation of a procedure to re-calibrate and/or create the trigger tables, Segment-specific deterioration curves, Family models, and Treatment Performance models and update the treatment selection process. The deliverable was the document describing the framework to develop the above process. The deliverable is included in Volume VII of the *MoDOT Preservation Research Project* report (Bowders et al. 2015). The sub-tasks are listed below.

1. Sub-task 6A: Search, compile and synthesize recent literature
2. Sub-task 6B: Gather, compile, and synthesize information from state DOTs
3. Sub-task 6C: MoDOT existing elements and processes
4. Sub-task 6D: Prepare draft concept and framework document
5. Sub-task 6E: Discuss and comment on draft framework document
6. Sub-task 6F: Prepare final framework document

3 TASK SUMMARIES: FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

3.1 Task 1: Historical Data Mining and Production of Data

- **Sub-task 1A:** *Conduct literature review:* The team reviewed reports from 15 state DOTs including Mississippi, Louisiana, Virginia, Colorado, and South Dakota. The literature review focused on data collection and organization as related to the different pavement families and family-treatments. A number of references and data products were organized at a common access Internet site called “www.ibackup.com”, which all investigators had access for data sharing during the project.

- **Sub-task 1B:** *Identify and access MoDOT (and non-MoDOT) data sources:* Raw or “unit” International Roughness Index (IRI) data was determined to be the only practical response variable currently in use by MoDOT that was available to the researchers for use in developing pavement performance and treatment impact models for prediction purposes. In addition to raw ARAN data, the research team successfully gathered data from MoDOT’s TMS (ARAN viewer, STIP, etc.), SS Pavement History data using ArcGIS software, TR50 traffic reports, project history maps (ragmaps), archived plan sheets folder, Central district pavement plan Excel files, and concrete summary (2-AA) and asphalt summary sheets. As a result of interviews with Brad Brown (Southwest District Pavement Specialist) and Joe Moore and Jason Schafer (Central District), a greater understanding of the pavement selection process and program planning at the District level was achieved for the various levels of traffic. This included the interplay of route AADT, treatment type, material type, projected treatment life, and available budget. The Task 1 team also learned about the part of the maintenance program that is uploaded to the Pavement Tool by the District. Additionally, as it became apparent that other information was needed for the model-building, data sources outside of MoDOT were accessed. For subgrade soils, the websites of the US Department of Agriculture (USDA) and Arizona State University (ASU) were utilized. For climate data, the National Oceanic and Atmospheric Administration (NOAA) website and AASHTOWare software were used.

- **Sub-task 1C:** *Retrieve pavement data for use by the subsequent tasks in this research project:* The MoDOT pavement data sources were used for collection of sufficient data for use by other tasks within the Pavement Preservation Research program, primarily by Task 2 (pavement family and treatment performance modeling) and Task 5 (treatment trigger and decision method development). The procedure for collecting data involved identifying homogenous sections meeting the criteria for each family (i.e. pavement type and traffic level), querying databases to collect raw data, verifying the raw data and supplementing it with pavement history (e.g. 2-AA sheets, asphalt summaries, STIP, etc.) and ARAN video observational data, and preparing the data for presentation to other tasks. This procedure was sufficient for the Pavement Preservation Research program data needs, but it was rather labor intensive, and efficiency improvements by MoDOT in the future would result in major time savings for an implemented pavement management system.

- **Sub-task 1D:** *Develop a methodology for data management:* The Task 1 document summarizes various MoDOT data sources and explains the procedures for gleaning useful modeling information from those sources. The report therefore draws on the experiences of Sub-tasks 1A through 1C. The report also summarizes the data collected and addresses the remaining data collection needs for an improved pavement management system. By documenting data sources, data collection procedures, and data collection needs, the report should be a useful tool for future development and improvement of MoDOT's Pavement Management System.

- **Sub-task 1E:** *Prepare Guidance Document:* Four of the five appendices to Volume II (Task 1) constitute the overall Guidance Document. Appendix B is the Guidance Document for data retrieval, Appendix C is the Guidance Document for creation and updating of models, Appendix D deals with subgrade soils data procurement, and Appendix E presents climate data retrieval.

3.2 Task 2: Family and Treatment Performance Models

- **Sub-task 2A:** *Conduct literature search:* Numerous publications were identified and procured in regard to other state DOTs' model development strategies, similar to those described in the Task 1 summary.

- **Sub-task 2B:** *Engage in significant discussions with MoDOT to obtain information needed to understand MoDOT's experience with performance modeling and their expectations for any newly developed models, create the pavement families, and compile the database into a usable format for model-building:* Team members met with and/or corresponded with MoDOT personnel at both the District and Central Office levels across three divisions in regard to pavement maintenance strategies/policies affecting potential pavement performance (deterioration) models and treatment impact models.

- **Sub-task 2C:** *Conduct development of pavement performance models and treatment impact models:* Based on data on minor routes from the Central District for Full-Depth Asphalt pavements and from six districts for Concrete and Composite pavements, six models were developed in Task 2 (Volume III) for prediction of IRI: three family models, for use as surrogates for specific route segment deterioration curves, and three treatment models: 1-in. HMA overlays on Full-Depth Asphalt pavements, 3¾-in. HMA overlays on concrete pavements (Composite pavements), and chip seals on Full-Depth Asphalt pavements. These models can be re-arranged to solve for Surface Age, which can be viewed as a prediction of service life at certain target terminal threshold IRIs (e.g. 140 and 170 in./mile). The variables in the models were those that the literature search predicted would be important: existing pre-treatment condition (IRI_t), initial condition after treatment (IRI_o), traffic (using Surface Age as a surrogate), climate (DT32, FT, DP01), subgrade soil (P200, Pclay), and last treatment thickness (LstTrtThk), as well as the relationship between IRI_o and IRI_t (IRI_{improv}). Regarding the parameters that did prove to be significant in predicting IRI, one should remember that the FDA data applied only to the Central District. Increasing the range of climate and subgrade soil parameter values by expanding the analyses to the entire state could not only improve the models but allow for additional parameters to play a role in predicting IRI. Although the Comp/PCC sections were selected from regions spread throughout the state, the number of homogenous sections was fairly limited which would also limit the probability of identifying additional parameters to predict IRI.

The data quality checks, reduction, and configuration in preparation for regression analyses were the most time-consuming portions of Task 2. Follow-up verification or determination of treatment type, thickness, etc., determination of a more accurate date corresponding to the opening of the pavement to traffic, and culling of invalid IRI data are activities that were tedious. Hopefully, this process will become more efficient through automation and/or the use of new methodologies by MoDOT, such as the Pavement Tool.

3.3 Task 3: Pavement Evaluation Tools-Data Collection Methods

- **Sub-task 3A:** *Summarize methods routinely used by MoDOT to assess pavement condition:* All districts were polled, and the information was compiled.
- **Sub-task 3B:** *Summarize commercially-available methods to assess pavement condition*: Commercially-available methods were investigated and summarized.
- **Sub-task 3C:** *Summarize methods currently being researched:* Eight NDE methods were researched and summarized.
- **Sub-task 3D:** *Comparative analysis of methods investigated:* A comparative analysis was completed.
- **Sub-task 3E:** *Method selection for Task 4:* Methods were selected to carry out the project-level and network-level investigations conducted in Task 4. Procurement and testing of air-launched GPR equipment (GSSI Roadscan 2 System – twin 2GHz Horn antennae) and GPS unit (Trimble GeoXH) was completed. Mounting of the GPR unit to the front of a vehicle was designed and fabricated, and the GPR unit was tested before acquiring the data in Task 4.

Based on the assessments conducted in this task, the non-invasive imaging technologies recommended for the Task 4 investigations are summarized in Table 3.1. These methods were selected to evaluate and demonstrate the applicability to project-level and/or network-level roadways.

Table 3.1 - Summary of non-invasive technologies from Task 3 recommended for Task 4 project-level and network-level investigations

Non-invasive Imaging Technology	Project-level Roadways	Network-level Roadways	ARAN compatible
Ultrasonic Surface Waves (USW)	Yes	No	No
Impact Echo (IE)	Yes	No	No
Ground-coupled Ground Penetrating Radar (GPR) (400 MHz and 1500 MHz)	Yes	No	Yes
Electrical Resistivity Tomography (ERT)	Yes	No	No
Multichannel Analyses of Surface Waves (MASW)	Yes	No	No
Falling Weight Deflectometer (FWD)	Yes	No	No
Rolling Dynamic Deflectometer (RDD)	Yes	No	No
Air-launched Ground Penetrating Radar (GPR)	No	Yes	Yes

In the Task 4 Appendix A Guidance Document, pavement-specific applications for each of the eight recommended non-invasive technologies are presented. Each of the recommended technologies could be utilized effectively by appropriately trained MoDOT personnel. Only two of the eight recommended technologies (ground-coupled GPR and air-launched GPR) are compatible with the ARAN vehicle. The ultrasonic surface wave, impact echo, ground penetrating radar and electrical resistivity tools are readily stored and can be transported to a work site in a pick-up truck. The falling weight deflectometer and rolling dynamic deflectometer require dedicated vehicles. The field data acquired using all eight technologies are readily processed using commercially-available software and a laptop or desktop computer. Although the literature indicated that ground-coupled GPR was not recommended as a network-level assessment tool, Task 4 decided to evaluate it for potential use.

The final report for this task presents comparative summaries of available technologies that can be used to collect data on pavement condition. The summary will be used to provide guidance to MoDOT on network-level or project-level data collection. Technologies were summarized in terms of applicability to network-level or project-level data production, types of pavement condition data collected (distress, structural capacity, surface characteristics), data collection method (manual, automated, semi-automated), and other advantages, disadvantages, and limitations. Descriptions of each technology were provided, in addition to current and previous usage by MoDOT and its contractors. Another summary table was developed to describe and compare the planning and cost-related aspects of each technology such as crew size, cost per day, area per day, lane closure requirements, level of expertise in data acquisition/processing, etc.

3.4 Task 4: Site Specific Condition Assessment

In Task 3, the following non-invasive technologies were identified as potentially most applicable to MoDOT roadways based on a review of published literature and the researchers' experience:

1. Ultrasonic Surface Waves (USW)
2. Impact Echo (IE)
3. Ground-coupled Ground Penetrating Radar (GPR) (400 MHz and 1500 MHz antennae)
4. Electrical Resistivity Tomography (ERT)
5. Multichannel Analyses of Surface Waves (MASW)
6. Falling Weight Deflectometer (FWD)
7. Rolling Dynamic Deflectometer (RDD)
8. Air-launched Ground Penetrating Radar (GPR)

In Task 4, to thoroughly assess the cost-effectiveness and utility of these technologies, corresponding field data were acquired across/along designated MoDOT roadways. Technologies 1-7 listed above were used to acquire non-invasive data along eight designated project-level roadways; technologies 3 (400 MHz only) and 8 listed above were used to acquire non-invasive data along two designated network-level roadways.

The primary survey objectives (as defined by MoDOT) and related positive outcomes for each of the tested project-level roadways are presented. Positive outcomes were realized by six of the seven technologies (1-7) applied to the project-level roadways. The only technology that did not consistently generate positive outcomes was Impact Echo (IE; technology 2 above). The IE tool is designed to automatically output reliable estimates of the thicknesses of pavement layers and the depths to defects within the pavement layers. Unfortunately, the depth estimates automatically output by the IE tool at the test locations were not reliable. Hence, the outcomes of the IE tool were not deemed to be positive.

The ultrasonic surface wave technology, in contrast, proved to be very useful. The USW tool automatically outputs 1-D plots of the dynamic elastic modulus of the pavements to maximum depths of approximately 11 in. These elastic modulus plots are reliable (according to published literature) for uniform pavements and for the uppermost layer of non-uniform (e.g. asphalt over concrete) pavements. Pavement layers with contrasting elastic moduli (e.g. asphalt over concrete) could be identified on the 1-D elastic modulus plots, and layer thicknesses could be estimated (to a maximum depth of approximately 11 in.). Zones of stripping in asphalt layers (where present) were characterized on the 1-D plots by anomalously low values of dynamic elastic modulus. The only significant disadvantages to using this tool are that lane closures are required, and data acquisition is relatively slow.

The interpretations of the higher-frequency (1500 MHz) ground-coupled GPR antenna data were also useful. Different pavement layers (maximum depths of approximately 18 in.) and joints could be mapped with confidence at all project-level pavement sites. The pattern, placement, and density of reinforcing steel could also be readily determined. At some sites, there is a statistical correlation between debonded interfaces (confirmed by limited core control) and corresponding GPR reflection amplitudes; at other sites it appears debonding could not be identified with confidence on the GPR profiles. However, core control was limited. In contrast, zones of stripping in asphalt layers (where present) could be visually identified on individual GPR profiles. Voids beneath segments of one tested segment of roadway could be mapped with apparent confidence (based on limited core and USW control). The only real significant disadvantage to using this tool is that lane closures are required. Data acquisition is relatively rapid.

The interpretations of the lower-frequency (400 MHz) ground-coupled GPR antenna data were somewhat less useful. This tool would be best used to image the base of thick pavements (greater than 18 in.) and base layers (to depths on the order of 4 ft). The only real significant disadvantage to using this tool is that lane closures are required. Data acquisition is relatively rapid.

At each project-level roadway site, both 2-D MASW and 2-D ERT data were acquired. It should be noted that the interpretation of the ERT and MASW data (in the absence of constraining core control) provided potentially very useful information at each project-level site. More specifically:

1. Top of weathered rock (where present) could be mapped on each 2-D ERT profile.
2. Top of intact rock (where present) could be mapped on each 2-D ERT profile.
3. Solution-widened joints (where present) could be mapped on each 2-D ERT profile.
4. Dry soil and moist soil could be differentiated on each 2-D ERT profile.
5. Moist clayey soil could be differentiated on each 2-D ERT profile.
6. Top of weathered rock (where present) could be mapped on each 2-D MASW profile.
7. Top of intact rock (where present) could be mapped on each 2-D MASW profile.
8. Lateral and vertical variations in the shear-wave velocity of soil and rock (where present) could be mapped on each 2-D MASW profile.

The positive outcomes of the MASW and ERT surveys are listed above because they may be unrelated to the primary survey objectives. The only significant disadvantages to using the MASW tool in the manner utilized for Task 4 investigations are that lane closures are required, and data acquisition is relatively slow. The only real significant disadvantage to using the ERT tool in the manner utilized for Task 4 investigations is that data acquisition is relatively slow.

The FWD is a well-established technique for pavement testing. The FWD provides useful information on the structural performance of both rigid and flexible pavements by measuring the deflection bowl produced from an impact load on the pavement surface. One of the advantages of the FWD is that it tests the pavements at strain levels that are similar to those experienced in service. The deflection measurements can be used in a variety of ways, including: to qualitatively assess support conditions, to estimate stiffness parameters using empirical relationships, to calculate load transfer efficiency across joints, and to back-calculate stiffness parameters through inversion analyses. The primary disadvantages of the FWD for pavement management applications are the point-by-point nature of the measurement, which limits its coverage for pavement management applications, and the time consuming analysis to back-calculate stiffness parameters.

The interpretations of the RDD data provided useful information about the pavement systems tested in this study. The unique high spatial-resolution (2 to 3 ft intervals) view of the pavement deflection profile provided by the RDD is not practically obtainable with existing technologies. The RDD appears to be most useful when applied to rigid pavements, particularly for assessing the quality of joints. Deflection measurements can be used to determine load transfer efficiency across joints and cracks, and due to the continuous nature of the RDD measurement, it is possible to test every joint. At the current stage of development, the utility of the RDD for flexible pavements is largely as a means to qualitatively assess pavement support conditions. The deflection measurements from the RDD do not appear to be sufficiently sensitive to debonding and stripping within the surface materials. The ability to perform measurements at 1 to 2 mph allows for extensive coverage of pavements in a relatively short amount of time. The structural information from the RDD could be used to identify regions in need of further study (due to anomalously high deflections) or to develop and apply more site specific rehabilitation strategies based on structural performance. In addition, the RDD could be used as an effective quality control tool to evaluate newly constructed or rehabilitated pavements. The RDD requires lane closures, although it can be performed using moving lane closures in some cases.

To thoroughly assess the cost-effectiveness and utility of technologies 3 and 8, lower-frequency (400 MHz) and high-frequency (2000 MHz) air-launched GPR data were acquired along two designated MoDOT network-level roadways. In Table 3.2, the primary survey objectives (as defined by MoDOT) and related positive outcomes for each of the tested project-level roadways are presented.

The interpretations of the high-frequency (2000 MHz) air-launched GPR data were useful. Pavement layers (maximum depths of approximately 18 in.) could be mapped with confidence at both network-level pavement sites (Table 3.3). The lower-frequency (400 MHz) antenna data could be used to image the pavement (and sub-pavement where applicable) to depths on the order of 4 ft. There are no significant disadvantages to acquiring network-level GPR data using truck mounted antennae.

A key deliverable from Task 4 is a guidance document focused on the utility and cost-effectiveness of project-applicable and network-applicable non-invasive imaging technologies. The guidance document is presented in Appendix A of Volume V.

Table 3.2 — Positive outcomes from the eight project-level site investigations

Project-level Roadway	Primary Survey Objective(s)	Positive Outcomes
US 63 Phelps County (Site 1)	Estimate pavement thickness and assess roadway condition	1. USW tool could be used to estimate layer thicknesses (to a maximum depth of approx. 11 in.). 2. USW tool could be used to assess the actual concrete (PCC) and/or relative bituminous material (BM) condition of the pavement (to a maximum depth of approx. 11 in.). 3. Higher-frequency (1500 MHz) GPR tool could be used to estimate layer thicknesses (to base of lower PCC layer). 4. Higher-frequency (1500 MHz) GPR tool could be used to image wire mesh and joints. 5. Lower-frequency (400 MHz) GPR tool could be used to image joints and pavement to depths of approx. 4 ft. 6. RDD tool could be used to detect and test concrete joints and qualitatively assess pavement support conditions. High-deflection regions along the profile could be identified. 7. FWD tool could be used to test concrete joints, but the location had to be known a priori (due to the BM cover). FWD deflections could also be used to qualitatively assess support conditions.
US 54 Camden County (Site 2)	Detect deep (>6 in.) stripping layer and assess roadway condition	1. USW tool could be used to estimate layer thicknesses (to a maximum depth of approx. 11 in.). 2. USW tool could be used to assess the condition of the BM pavement (to a maximum depth of approx. 11 in.). Zones of stripping were identifiable. 3. Higher-frequency (1500 MHz) GPR tool could be used to estimate layer thicknesses (to base of BM). 4. Higher-frequency (1500 MHz) GPR tool could be used to image debonding/stripping. 5. Lower-frequency (400 MHz) GPR tool could be used to image pavement to depths of approx. 4 ft. 6. RDD tool could be used to qualitatively assess pavement support conditions (with high spatial resolution) and identify regions with anomalously high deflections. 7. FWD tool could be used to assess pavement deflections at discrete points along the profile. The deflections could be used to estimate pavement stiffness parameters using empirical relationships.
Rte 179 Cole County (Site 3)	Detect debonding and assess roadway condition	1. USW tool could be used to estimate layer thicknesses (to a maximum depth of approx. 11 in.). 2. USW tool could be used to assess the condition of the BM pavement (to a maximum depth of approx. 11 in.).

		Zones of stripping and debonding were identifiable. 3. Higher-frequency (1500 MHz) GPR tool could be used to estimate layer thicknesses (to base of BM). 4. Higher-frequency (1500 MHz) GPR tool could be used to image debonding/stripping. 5. Lower-frequency (400 MHz) GPR tool could be used to image pavement to depths of approx. 4 ft. 6. RDD tool could be used to qualitatively assess pavement support conditions (with high spatial resolution) and identify regions with anomalously high deflections. 7. FWD tool could be used to assess pavement deflections at discrete points along the profile. The deflections could be used to estimate pavement stiffness parameters using empirical relationships.
HWY AT Franklin County (Site 4)	Detect shallow (<6 in.) stripping layer and assess roadway condition	1. USW tool could be used to estimate layer thicknesses (to a maximum depth of approx. 11 in.). 2. USW tool could be used to assess the condition of the BM pavement (to a maximum depth of approx. 11 in.). Zones of stripping were identifiable. 3. Higher-frequency (1500 MHz) GPR tool could be used to estimate layer thicknesses (to base of BM). 4. Higher-frequency (1500 MHz) GPR tool could be used to image debonding/stripping. 5. Lower-frequency (400 MHz) GPR tool could be used to image pavement to depths of approx. 4 ft. 6. FWD tool could be used to assess pavement deflections at discrete points along the profile. The deflections could be used to estimate pavement stiffness parameters using empirical relationships.
I-55 Pemiscot County (Site 5)	Assess an unbonded concrete overlay (no flaws anticipated)	1. USW tool could be used to estimate layer thicknesses (to a maximum depth of approx. 11 in.). 2. USW tool could be used to assess actual (PCC) and/or relative (BM) condition of pavement (to a maximum depth of approx. 11 in.). Zones of stripping were identifiable. 3. Higher-frequency (1500 MHz) GPR tool could be used to estimate layer thicknesses (to base of PCC). 4. Lower-frequency (400 MHz) GPR tool could be used to image pavement to depths of approx. 4 ft. 5. RDD tool could be used to qualitatively assess pavement support conditions (with high spatial resolution) and identify high-deflection regions. Detection of individual joints was not possible in the 1000-ft section. 6. FWD tool could be used to determine load transfer efficiency across concrete joints.

I-55 Perry County (Site 6)	Assess joint condition	1. USW tool could be used to estimate layer thicknesses (to a maximum depth of approx. 11 in.). 2. USW tool could be used to assess the condition of the pavement (to a maximum depth of approx. 11 in.). 3. USW tool could be used to locate sub-PCC slab voids. 4. Higher-frequency (1500 MHz) GPR tool could be used to estimate layer thicknesses (to base of PCC). 5. Higher-frequency (1500 MHz) GPR tool could be used to locate sub-PCC slab voids. 6. Higher-frequency (1500 MHz) GPR tool could be used to image wire mesh and joints. 7. Lower-frequency (400 MHz) GPR tool could be used to image pavement to depths of approx. 4 ft.
HWY U Dent County (Site 7)	Assess a poor-condition asphalt roadway	1. USW tool could be used to estimate layer thicknesses (to a maximum depth of approx. 11 in.). 2. USW tool could be used to assess the condition of the BM pavement (to a maximum depth of approx. 11 in.). Zones of stripping were identifiable. 3. Higher-frequency (1500 MHz) GPR tool could be used to estimate layer thicknesses (to base of BM). 4. Higher-frequency (1500 MHz) GPR tool could be used to image debonding/stripping. 5. Lower-frequency (400 MHz) GPR tool could be used to image pavement to depths of approx. 4 ft. 6. FWD tool could be used to assess pavement deflections at discrete points along the profile. The deflections could be used to estimate pavement stiffness parameters using empirical relationships.
I-35 Jackson County (Site 8)	Assess an unbonded concrete overlay (flaws are anticipated)	1. USW tool could be used to estimate layer thicknesses (to a maximum depth of approx. 11 in.). 2. USW tool could be used to assess actual and/or relative condition pavement (to a maximum depth of approx. 11 in.). 3. Higher-frequency (1500 MHz) GPR tool could be used to estimate layer thicknesses (to base of lower PCC layer). 4. Higher-frequency (1500 MHz) GPR tool could be used to image wire mesh and joints. 5. Lower-frequency (400 MHz) GPR tool could be used to image joints and pavement to depths of approx. 4 ft. 6. RDD tool could be used to test concrete joints and qualitatively assess support conditions. High-deflection regions along the profile were identified. 7. FWD tool could be used to determine load transfer across concrete joints and qualitatively assess support conditions.

Table 3.3 – High-frequency air-launched GPR

Recommendations	For a regional-level site investigation where the intent is to image BM and/or PCC a GPR system with a high-frequency air-launched antenna (2 GHz) is recommended.
Capabilities	1. Tool can be used to measure thicknesses of existing pavement layer with an accuracy of ± 10% if core control is available. 2. Tool can be used to estimate the thicknesses of new pavement layers with a higher degree of accuracy. 3. Tool can be used to accurately locate pattern, placement and density of reinforcing steel, wire mesh and dowel bars. 4. Tool can be used to locate joints. 5. Tool can be used to locate shallow utilities (embedded within pavement or immediately below pavement). 6. Tool can be used to identify areas of deteriorated bituminous mix pavement, especially if the BM pavement thickness is known or uniform, or if stripping and/or delaminations are present. 7. Tool can be used to identify deteriorated Portland cement concrete pavement, especially if the pavement thickness is known or uniform. 8. Tool can be used to image shallow voids immediately beneath pavement. 9. Tool can be used to map (qualitatively) variations in the moisture content of soil immediately beneath uniform pavement. 10. Tool can be used for QA/QC of new pavement.
Parameters measured and/or displayed	GPR systems are designed to generate visual displays depicting the arrival times and amplitudes of signal reflected from within the pavement. Reflectors include all pavement layers (top, base, PCC/BM, BM/PCC, BM/BM), delaminations, stripping, reinforcing steel, wire mesh, dowel bars, utilities and joints.
How these parameters relate to condition of roadway	The amplitude of a reflection from a pavement layer is a function of the nature of the interface, the condition of the interface and the condition of the overlying pavement. Lateral variations in the condition of the interface and/or the condition of the overlying pavement cause corresponding changes in the amplitude of the reflection from that interface. Often, these amplitude variations can be measured, plotted and interpreted. The arrival time of a reflection from a pavement layer is a function of the nature of the interface, the condition of the interface and the condition of the overlying pavement. Lateral variations in the condition of the interface and/or the condition of the overlying pavement cause corresponding changes in the arrival time of the reflection from that interface. Often, these arrival time variations can be measured, plotted and interpreted. Reflection amplitudes and arrival times will also change if the depth to the interface changes (e.g. variations in pavement thickness). If pavement thicknesses are not uniform, it can be difficult to confidently identify the cause of plotted amplitude and/or travel time variations. Reflections can also be generated by stripping, delaminations, voids, utilities, reinforcing steel, dowel bars, wire mesh and utilities. These can often be confidently identified by an experienced interpreter.
Optimum acquisition	Air-launched high-frequency GPR data are normally acquired in a fast moving

parameters	(highway speeds) vehicle. Acquisition parameters (including speed) depend on target size. If small targets (reinforcing steel) is to be imaged, denser sampling intervals (trace spacing) and slower vehicle speeds are required.
Optimum weather conditions	Intact and deteriorated pavements are easiest to differentiate if moisture is present. GPR data acquired when the pavement is slightly moist are more interpretable and more definitive (re: pavement condition). Pavement layer thicknesses can be estimated during any weather condition (core control will result in more accurate estimates). Similarly, reinforcing steel, wire mesh, dowel bars, utilities, voids, stripping, can be mapped during all weather conditions.
Crew size	Typically 2 persons; a driver and an operator.
Equipment costs (2015)	An air-launched GPR system with a twin 2-GHz antennae and all mounts costs about $80,000.
Volume of data that can be acquired in 8 hour day	A 2-person field crew using a commercial vehicle can acquire air-launched GPR data at highway speeds.
Potential acquisition problems	The operator must be able to mount both the GPR and GPS systems on the vehicle and interface the data.
Optimum processing parameters	Generally, only basic processing is required. A trained processor is required.
Software and hardware costs (2015)	Commercial processing/interpretation software is about $5000.
Volume of data that can be processed in an 8-hour day	Depends on the data quality and pavement condition. Frequently about 5,000+ lineal ft of GPR data can be processed in one day. The processing of GPR data acquired across multi-layered pavement or poor-quality pavement is slower and requires greater expertise.
Ease of processing	An experienced processor is required. The processing of GPR data acquired across multi-layered pavement or poor-quality pavement requires greater expertise. Generally, the processor interprets the GPR data.
Potential processing problems	Poor quality data can be difficult to process. The conversion of reflection times to depths is very approximate unless ground truth (core control normally) is available.
Optimum interpretation parameters	Ideally, the processor should be able to plot (on a base map) the amplitudes and apparent depths of all reflectors of interest.
Volume of data that can be interpreted in an 8-hour day	Depends on the data quality and pavement condition. If ground truth is available, a skilled interpreter (normally the processor) can normally assess large volumes of mapped amplitude and apparent depth data in a few hours.
Deliverables	A suite of maps showing variations in the amplitudes and apparent depths of reflectors of interest with superposed interpretations and highlighted features of interest.
Ease and reliability of interpretations	If ground truth is available, a skilled processor/interpreter will generate very reliable interpretations.
Potential interpretation problems	Interpretations are non-unique and can be somewhat ambiguous if additional data are not available (e.g. ground truth).

Recommendations (including practices that could help MoDOT; cost-effectiveness)	The high-frequency air-launched GPR technology should be the primary tool of choice for the following network-level pavement condition assessment applications: • Tool can be used to measure thicknesses of existing pavement layers with an accuracy of ± 10% if core control is available. • Tool can be used to estimate the thicknesses of new pavement layers with a higher degree of accuracy. • Tool can be used to accurately locate pattern, placement and density of reinforcing steel, wire mesh and dowel bars. • Tool can be used to locate joints. • Tool can be used to locate shallow utilities (embedded within pavement or immediately below pavement). • Tool can be used to identify areas of deteriorated bituminous mix pavement, especially if the BM pavement thickness is known or is uniform, or if stripping and/or delaminations are present. • Tool can be used to identify deteriorated Portland cement concrete pavement, especially if the pavement thickness is known or is uniform. • Tool can be used to image shallow voids immediately beneath pavement. • Tool can be used to map (qualitatively) variations in the moisture content of soil immediately beneath uniform pavement. • Tool can be used for QA/QC of new pavement. Use of ground truth to constrain and verify interpretations will statistically improve the accuracy of the GPR interpretations. We recommend acquiring data using two air-launched GPR antennae.

Table 3.4 – Applications to assessment of bituminous mix (BM) pavements

	BM layer thicknesses	BM layer condition	Debonding	Stripping	Cracking	Segregation	Rutting	Corrugation	Shoving	Depression	Overlay bumps	Patching	Raveling	Moisture below BM	Voids	Shallow utilities	Delaminations
USW	d	D	i	I		I							I		I		I
IE																	
HF-GC-GPR	D	I	D	I		I							I	I	D		I
LF-GC-GPR	d	i												i	d	D	
HF-AL-GPR	D	I	D	D		I								I	D		I
FWD																	
RDD																	
ERT																	
MASW																	

USW: ultrasonic surface wave; IE: impact echo; HF-GC-GPR: high-frequency ground-coupled ground penetrating radar; LF-GC-GPR: low-frequency ground-coupled ground penetrating radar; HF-AL-GPR: high-frequency air-launched ground penetrating radar; FWD: falling weight deflectometer; RRD: rolling wheel deflectometer; ERT: electrical resistivity tomography; MASW: multi-channel analyses of surface waves). D–Direct Measurement/Primary Application; d–Direct Measurement/Non-primary Application; I–Indirect Measurement/Primary Application; i–Indirect Measurement/Non-primary Application.

3.5 Task 5: Pavement Treatment Trigger Tables/Decision Trees and Treatment Candidate Selection Process

- **Sub-task 5A:** *Procure laboratory equipment and AASHTOWare software:* Purchase or design and fabrication of the following was completed: Asphalt Mixture Performance Tester (AMPT), Asphalt Pavement Analyzer (APA) Hamburg and digital upgrade, Texas Overlay Jig, four conditioning ovens with support shelves, gyratory compactor mold spacers, gyratory compactor mold modification, core drill permanently mounting, core holding jig, and core holding saw jig. The AMPT compressor and Texas Overlay Jig eventually had to be replaced by the vendor.

- **Sub-task 5B:** *Conduct literature search:* The experience of other DOTs indicates that the factors that affect the *success* of pavement treatments are a function of the following:

    - Original pavement type
    - Layer thicknesses
    - Base characteristics, including internal drainage
    - Specific design features
    - Subgrade type
    - Condition prior to treatment
    - Initial condition after treatment
    - Quality of treatment
    - Climate
    - Accumulated traffic, especially truck traffic
    - Interim maintenance procedures

The search of other state DOT experiences and procedures (including the four states surrounding Missouri: Illinois, Arkansas, Kansas, and Iowa) resulted in tables of appropriate applications, expected treatment performance lives, costs, and methods to evaluate cost effectiveness. The factors that affect treatment *selection* are:

- Traffic
- Pavement condition
- Climate and weather
- Work zone restrictions
- Roadway geometrics
- Experience with treatment
- Availability of good quality materials
- Availability of specialized equipment and materials
- Environmental considerations
- Expected performance
- Available funding/cost

- **Sub-task 5C:** *Engage in discussions with MoDOT to obtain information about pavement types, treatment types, selection criteria, mixes, and past history:* The Task 5 team met with or held telephone/email conversations with a number of MoDOT personnel from different divisions one-on-one in regard to choice of mix designs, pavement maintenance policies, lab equipment, and subgrade soils data. From these discussions, decisions were made in choosing mix types to study in sub-task 5E.

- **Sub-task 5D:** *Conduct treatment option analysis using AASHTOWare:* The AASHTOWare treatment option analysis revealed the relative importance of several variables to 1-in. overlay pavement performance. The AASHTOWare analysis of the longevity of 1-in. surface leveling mixes showed that the program considered initial IRI after treatment the most significant factor, along with existing roadway condition and AADTT. Other factors that were important to a lesser extent were climate, subgrade, existing thickness, and overlay quality. Considering the variable types and ranges of input used in the analysis, the overall average life of 1-in. overlays across the state was predicted as 12.5 years. In a comparison to actual MoDOT overlays, the software tended to significantly overestimate overlay life. The overlay lives predicted from AASHTOWare cannot be used for trigger tables per se, but the insight provided by the analysis is useful for creating an evaluation system.

- **Sub-task 5E:** *Conduct mixture testing and analysis:* In regard to pavement treatment evaluation, longevity of various treatments must be predicted. The objective of Sub-task 5E was to perform laboratory testing of HMA mix types in order to use results of performance testing, such as Hamburg Loaded Wheel rutting/stripping characteristics and Tensile Strength Ratio (TSR), to assess the effect of mix characteristics on rutting and stripping. The general approach was to narrow the scope of HMA mix types to be evaluated to those that would be used for maintenance on minor routes. After discussions with MoDOT personnel, it was decided to eliminate Superpave and BP-3 mixes and concentrate on surface leveling (SL) and other Bituminous Pavement (BP) mixes. Because SL and BP-2 mixes are virtually the same in many cases, the final experimental design called for BP-1 and SL mix types.

  Three levels of quality (Good, Marginal (In-Spec), and Marginal In-Tolerance (Out-of-Spec)) per mix type were evaluated to give a range of behavior. “Good” meant high quality aggregate, proper volumetrics, proper binder content, proper dust/effective binder ratio, minimal deleterious materials content, and so forth. “Marginal (In-Spec)” related to those attributes being barely approved in design. The in-tolerance out-of-specification mix was similar to the in-spec mix, but with several mix components allowed to stray as if during production: the dust was increased to the specification maximum allowable, the gradation became finer, the binder content was reduced, which led to lower (out-of-specification) air voids and VMA and a high dust/effective binder ratio. All mix designs approved by MoDOT’s field office in 2011 of SL, BP-1, BP-2, and bituminous base (BB) were examined as well as aggregate quality records. Two aggregate sources (formations/ledges) were chosen. The binder for all mixes was a PG64-22 (one supplier).

The mixes were subjected to Hamburg Loaded Wheel and TSR testing. The Texas DOT criteria for limestone mixes with a non-modified binder PG 64-22 (similar to MoDOT's BP plant mixes) is equal to or less than 12.5 mm rutting at 5000 cycles. The Good mix met this requirement with about 5550 cycles at 12.5 mm rut depth. Very little stripping was observed by visual inspection. The TSR for the Good mix was 86, well over the MoDOT section 401 minimum requirement of 70. For the Marginal (In-Spec) mix, the Hamburg results showed about 3040 cycles at 12.5 mm, failing the Texas DOT threshold. The TSR was 28, badly failing MoDOT's section 401 specification. The visual exam showed a loss of matrix and considerable broken aggregate. As expected, the Marginal In-Tolerance (Out-of-Specification) mix fared worse than the In-Specification mix: the Hamburg results resulted in about 2440 cycles at 12.5 mm, failing the Texas DOT threshold. The TSR was 23, badly failing MoDOT's section 401 specification. The visual exam showed a loss of matrix and considerable broken aggregate. Hamburg Loaded Wheel Tester and TSR laboratory tests of rutting and stripping showed that marginal and poor quality BP-1 mixes lasted 54% and 44% as long as a good quality mix, respectively. The number of Hamburg load applications to failure cannot be used directly for trigger tables per se, but the insight provided by the analysis is useful for creating an evaluation system. The quality of the overlay mix was shown to be more important to longevity than the AASHTOWare analysis implied. Unfortunately, MoDOT specifications for surface leveling and plant mixes underwent a continuous series of changes since the project was conceived in 2011. After the initial round of testing, MoDOT Research and Missouri S&T agreed to cease further testing until the effects of the changes were better defined and that the changes would settle down before testing resumed on the surface leveling mixes in a subsequent project.

- **Sub-task 5F:** *Create a draft manual of treatment trigger table/decision trees and cost effectiveness procedure:* Six models were developed in Task 2 (Volume III) for prediction of IRI: three Family models, for use as surrogates for Segment-specific route deterioration curves in cost effectiveness calculations, and three Treatment Performance models, for prediction of service lives in cost effectiveness analyses: 1-in. HMA overlays on Full-Depth Asphalt pavements, 3¾-in. HMA overlays on concrete pavements (Composite pavements), and chip seals on Full-Depth Asphalt pavements. These models can be re-arranged to solve for Surface Age, which can be viewed as a prediction of service life at certain target terminal threshold IRIs (e.g. 140 and 170 in./mile). The variables in the models were those that the literature search predicted would be important: existing pre-treatment condition (IRI_t), initial condition after treatment (IRI_o), traffic (using Surface Age as a surrogate), climate (DT32, FT, DP01), subgrade soil (P200, Pclay), and last treatment thickness (LstTrtThk), as well as the relationship between IRI_o and IRI_t. DT32 refers to number of freezing days per year, FT is the number of freeze-thaw cycles per year, DP01 means number of days of at least 0.1 in. rainfall per year, P200 is the percent minus #200 sieve material, and Pclay is the percent clay-size material in the subgrade soil.

  The general approach to treatment selection recommended herein is: for a given project, knowing IRI and Pavement Surface Evaluation and Rating (PASER) rating, several candidate treatment types are determined. Then, from a visual survey of the proposed project roadway, using the trigger tables developed in this report, treatments that are not appropriate for the specific distress types, extents, and severities are discarded, thus narrowing the number of candidate treatments. Finally, using a cost effectiveness approach, the remaining treatments are ranked.

The trigger tables are used in series. One table was developed from MoDOT's treatment decision tree in MoDOT's *Engineering Policy Guide* (EPG) plus the decision matrix from MoDOT's *Pavement Maintenance Direction* report. The *EPG* and the *Direction* were reconciled with each other and with pavement field data gathered for use in Task 2. Once the general type(s) of treatments are determined from the table, a second table derived from other states' experiences is used to choose treatments tailored to specific distresses. The list of specific candidate treatments is narrowed to those that are appropriate for all the distresses. Finally, a cost effectiveness analysis is done. Several approaches are presented, including Equivalent Annual Cost (EAC), Remaining Service Life (RSL), and Benefit-Cost ratio (B/C). The last is probably the best, but usually requires the use of software.

Ideally, all MoDOT routes should eventually be divided into homogeneous sections (segments). Each roadway section would have its own condition plots for IRI and PASER rating deterioration. The fitted curves can be extended to the action threshold of choice; for example, one commonly used threshold is where reconstruction is the only option. Each curve would be constructed from real IRI or PASER data. In use, when a section is being analyzed for a life cycle-type analysis, the deterioration curves plus a variety of possible treatment strategies would be plotted over an analysis period of, say, 30 years. When available, a PASER rating deterioration curve would also be constructed for the segment, and Remaining Service Life before treatment (RSL_{BT}) determined for each of the two curves (IRI and PASER). The shortest RSL would be chosen with which to go forward (see below).

Sometimes, however, there will not be sufficient data to plot a segment-specific curve, especially in the early going of setting up this part of a PMS. In order to plot a real-data curve, the Colorado DOT (2011) recommends at least five condition points, with an R^2 of at least 0.50. So, in the case of an insufficient number of points, in lieu of a "real" curve, a Family curve can be substituted until sufficient data is available. The Family curve is one fitted to many other similar sections. In the present study, Family curves have been presented for Full-Depth Asphalt, Composite, and Concrete pavements. For instance, the model for the Full-Depth Asphalt Family can be used for a given asphalt route's homogeneous section; the IRI prediction for 1-in. overlays will be tailored to that section via local FT, Pclay, LstTrtThk, IRI_t, and IRI_o data.

Either way (Family curve or segment-specific curve), once the IRI-time curve is plotted and extended to the threshold of choice (IRI_T), the analysis for treatment life can be done—this can be used later in EAC, B/C, or RSL cost-effectiveness calculations. Various treatment strategies can be tried (e.g. an initial 1-in. overlay at the beginning of the analysis period, a chip seal at 8 years, another 1-in. overlay at 12 years, and so forth. RSL_{BT}, Remaining Service Life after treatment (RSL_{AT}), and Service Life Extension (SLE) can then be calculated: ($SLE = RSL_{AT} – ESL_{BT}$). Then an EAC or B/C analysis performed.

Then another treatment strategy can be tried, and a B/C analysis done again. Finally the alternate strategies' B/Cs are compared, and one treatment chosen, typically for the greatest B/C. If one is analyzing a lot of routes and strategies, it will become necessary to invoke the use of a software program specifically designed to do this. These programs (such as Deighton's dTIMS) are capable of optimizing the selection, based on such methods as an "incremental B/C" analysis. This level of analysis is beyond the scope of this study.

The following is the procedure that a MoDOT Pavement Engineer or Pavement Specialist would use for implementing the *modified pavement management flowchart* (Fig. 2.1). The procedure would be followed for a given proposed road maintenance/preservation/rehabilitation project. The word "retrieve" is used to emphasize that the data, models, and tables to be used would already exist:

Step 1- Retrieve annual road condition survey (e.g. ARAN) data

Step 2- Retrieve site historical data: e.g. materials, thicknesses, subgrade soil, drainage, weather, construction records, etc.

Step 3- Retrieve traffic counts: Average Daily Traffic (ADT) and percentage trucks, or Average Daily Truck Traffic (ADTT) or Commercial Truck Volume

Step 4- Conduct a site-specific condition survey (visual, coring, non-destructive testing)

Step 5- Combine information from steps 1 through 4 into a "Site Status" report. Identify the roadway as a certain "Pavement Family" type (see Table 2.1)

Step 6- With "Site Status", enter appropriate Treatment Trigger Tables and select several alternate treatments (Table 2.2) appropriate for the roadway segment (or assigned Family)

Step 7- With the appropriate "Treatment Impact (Performance) Models," conduct a cost effectiveness analysis for each potential treatment. Choose the final treatment.

Step 8- Using the calculated cost effectiveness of all treatments and all projects, conduct a network-level (county, region or state-wide) project prioritization list. Project prioritization could be based on other considerations in addition to cost effectiveness

3.6 Task 6: Re-Calibration of Triggers and Performance Models

- **Sub-task 6A:** *Search, Compilation and Synthesis of Recent Literature:* Literature review efforts examined examples from other states. In particular, the team reviewed reports from Kansas, Virginia, Oklahoma, and South Dakota. The literature review focused on pavement condition assessment, how the assessment is used in pavement modeling, and especially how the models are updated.

- **Sub-task 6B:** *Information Gathering, Compilation and Synthesis from State DOTs:* Work on the literature review of Sub-task 6A narrowed down the list of potential states for further study related to pavement model updating procedures. The Task 6 team reached out to Michigan and Kansas DOTs to discuss their pavement model updating procedures. Both states sent reports that have been reviewed by the Task 6 team. The reports seem to indicate the models used for each state's respective pavement management system have been verified but not explicitly updated as new data are collected. In addition, the Task 6 team reviewed a report addressing model updating by CALTRANS.

- **Sub-task 6C:** *MoDOT Existing Elements and Processes:* The Task 6 team has discussed with MoDOT the models used in the pavement tool that was developed for MoDOT. One main objective of the pavement tool is to plan future maintenance treatments. Consistent with this objective, the models are simply predictions of treatment lifespan. The team discussed with the Planning Division of MoDOT the possibility of incorporating models from the Pavement Preservation project (Tasks 2 and 5) into MoDOT's Pavement Tool.

Sub-tasks 6D through 6F: *Preparation of Draft and Final Documents:* The report summarized the need for updating the models developed in Task 2 and used in Task 5. There were three Family models: Full-Depth Asphalt, Concrete, and Composite as well as three Treatment Performance models: 1-in. overlays on asphalt, chip seals on asphalt, and thin structural overlays on concrete or composite. Recommendations for future enhancements of the necessary data were presented. The necessity for creation of new models was emphasized: Segment-specific models, new Family models, and additional Treatment Performance models. Updating the trigger tables (created in Task 5) was also discussed. Finally, a detailed list of obstacles to data mining and handling with possible solutions was offered.

The procedure for creation of performance models was summarized in a figure in Volume II and was presented in the Task 6 report as well, shown as Fig. 3.1 below.

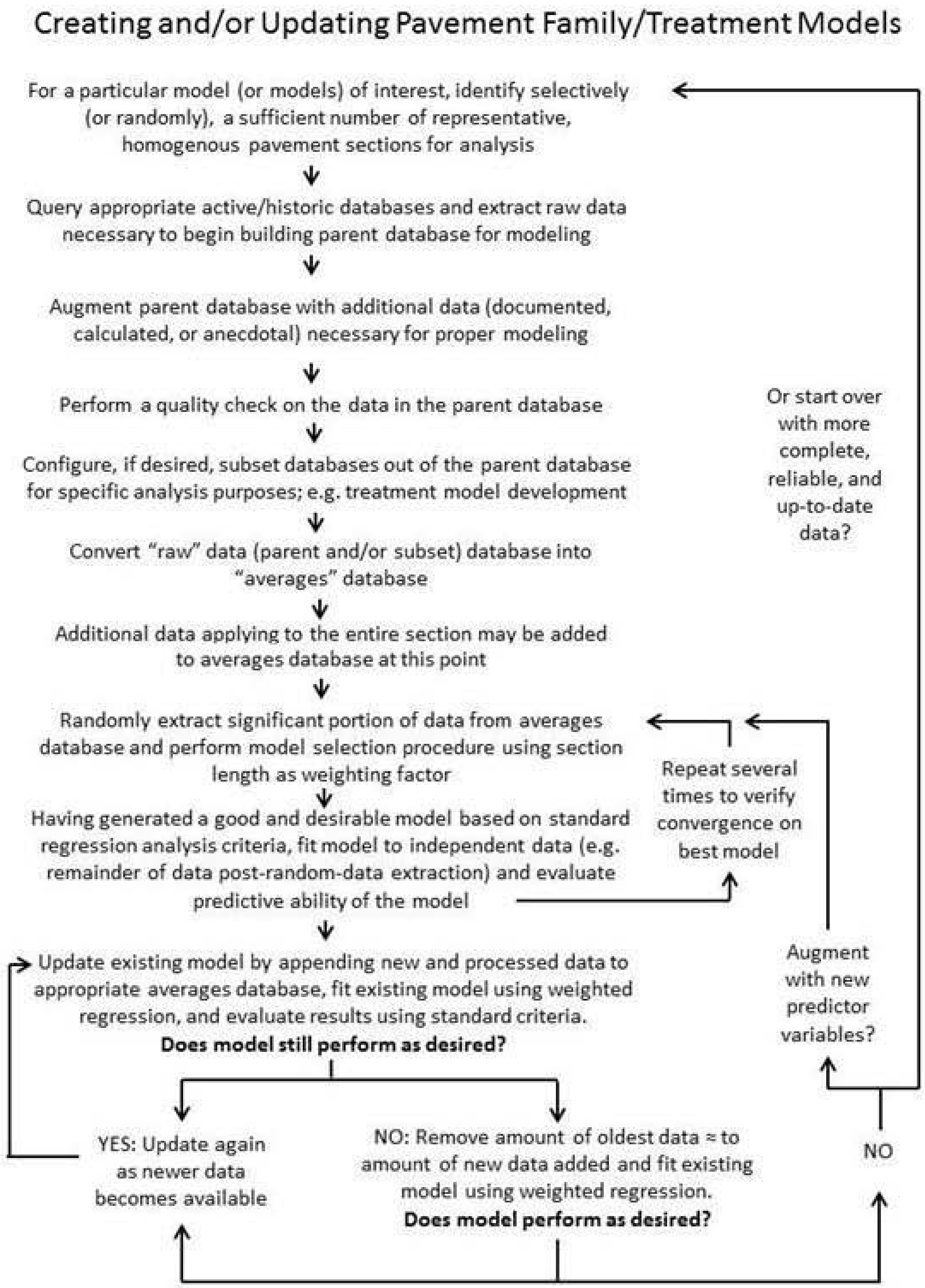

Fig. 3.1 – Flowchart for model updating.

Ideally, all MoDOT routes will eventually be divided into homogeneous sections, and there would be no need for Family models. Each roadway segment would have its own condition plots of real data for IRI deterioration. In use, when a segment is being analyzed for a life cycle-type analysis, the IRI deterioration curve plus a variety of possible treatment strategies would be plotted over an analysis period of, say, 30 years. In addition to IRI data, in the future when sufficient PASER data is available, a PASER rating deterioration curve would also be constructed for the segment, and RSL determined (if desired) for each of the two performance curves. The shortest RSL would be chosen with which to go forward.

Sometimes, however, there will not be sufficient data to plot a Segment-specific curve, especially in the early going of setting up this part of a PMS. In order to plot a Segment-specific curve, the Colorado DOT recommends at least five condition points, with an R^2 of at least 0.50. So, in the case of an insufficient number of points, in lieu of a "real" curve, a Family curve can be substituted until sufficient data is available. The Family curve is one fitted to many other similar sections. In the present study, Family curves have been presented for Full-Depth Asphalt, Composite, and Concrete pavements. Because there was not enough data available to create Segment-specific curves at the time of this study, only Family and Treatment Performance models were developed, thus Fig. 3.1 refers to Family and Treatment Performance models only.

The Task 5 report makes the following recommendations for creation of new models:

1. In regard to thin overlays, the data available for this report was constrained to 1-in. Section 402 surface leveling mixes on Full-Depth Asphalt pavements. As data becomes available, models should be developed for 1¼-in. and 1¾-in. Section 401 plant mix mixtures.
2. In regard to structural overlays, the data available for this report was constrained to 3¾-in. Section 401 plant mixes and 403 Superpave mixes on concrete pavements (thus Composite pavements). As data becomes available, models should be developed for thicker overlays on Concrete and Composite pavements.
3. In regard to surface treatments, the data available for this report was constrained to single chip seals on Full-Depth Asphalt pavements. As data becomes available, models should be developed for double chip seals, slurry seals, micro-surfacing, UBAWS, polymer chip seals, scrub seals, and scratch-and seal applications on Full-Depth Asphalt pavements. The same type of surface treatment models should be developed for Composite pavements as appropriate.
4. All routes should be divided into homogeneous sections. Annual IRI and PASER data should be collected, cleansed, and made available as presented in Appendix C of Volume II (Task 1) and Volume III (Task 2). Quality Assurance (QA) on the data can be done in a method similar to that described in Appendix B of Colorado DOT's PMS manual (Colorado 2011). Segment-specific IRI and PASER deterioration curves should be developed for each section. Where sufficient data is not available, Family models can be substituted as surrogates until sufficient data is available. RSLs should be calculated, and used in a system such as an SLE comparison, or an incremental B/C method for ranking treatments at the project level, and possibly at the network level. This would entail developing or acquiring software specific to this purpose.

   More family models should be developed as necessary.

4 SUMMARY and RECOMMENDATIONS

The "*MoDOT Pavement Preservation Research Program*" report documents a research project on pavement preservation performed by the Missouri University of Science and Technology (Missouri S&T) and the University of Missouri-Columbia (UMC) on behalf of the Missouri Department of Transportation (MoDOT). The report consists of a Summary Report followed by six detailed technical reports. The overall objective of the research was to provide a *process* that would allow MoDOT to do more selective planning, better engineering and more effective maintenance to minimize costs while maintaining adequate safety and performance of Missouri's pavements. Six Guidance Documents were created which will act as guidelines for MoDOT's Pavement Specialists and Pavement Engineers. The work was divided into six tasks, each with its own research (task) team. The focus of the research was on *preservation strategies* applied to *minor* routes.

Task 1: The research reported in the Task 1 document was performed by researchers from Missouri S&T and UMC. The objective of Task 1: *Data Collection for Pavement Management: Historical Data Mining and Production of Data* was to develop data for use in MoDOT's pavement preservation program based primarily on historical information available throughout MoDOT, as well as climate data from the National Oceanic and Atmospheric Administration (NOAA) and AASHTOWare (AASHTO), and subgrade soils data from the US Department of Agriculture (USDA) and the Arizona State University (ASU) websites. A pilot database, based on minor routes in the Central District for Full-Depth Asphalt pavements and in six districts for Concrete and Composite pavements, was developed to demonstrate the methodology for future use by MoDOT and for initial use by investigators in Tasks 2 through 6. Numerous databases maintained by MoDOT as well as climate and soils data from other sources were located, collected, supplemented, cleansed, verified, and summarized. Recommendations for changes to MoDOT's present data collection procedures and repositories were developed.

Task 2: The research reported in the Task 2 document was performed by researchers from Missouri S&T. The general objective of Task 2: *Development of Pavement Family and Treatment Performance Models* was to develop performance models for a variety of pavement families and pavement preservation treatments used by MoDOT. Ideally, all MoDOT routes will eventually be divided into homogeneous sections (segments). Each roadway section will have its own condition plots for IRI and PASER rating deterioration. The fitted curves can be extended to the action threshold of choice; for example, one commonly used threshold is where reconstruction is the only option. Sometimes, however, there will not be sufficient data to plot a segment-specific curve, especially in the early going of creating this part of a Pavement Management System. Thus, Family models will initially be used as surrogates for Segment-specific curves. A Family curve is one that is fitted to many other similar sections.

Using the data collected in Task 1, linear least-squares regression techniques were used to generate deterministic models that predict the IRI, the pavement condition measure most widely in use today. There was insufficient data available for the recently-adopted PASER overall condition index to develop models. Family IRI-prediction models were developed for full-depth asphalt (FDA), concrete (PCC), and composite (Comp) pavements. Treatment IRI-prediction models were developed for 1-in. overlays on FDA pavements, chip seals on FDA pavements, and 3¾-in. overlays on PCC pavement.

Predictor variables consistently shown to be highly significant in predicting IRI for both FDA asphalt and Comp pavements were initial IRI (IRI_o which is the IRI value right after treatment) and pavement Surface Age (SA). The majority of the PCC pavement sections selected were so old that IRI_o could not be determined (or estimated with any confidence), therefore SA was the dominant predictor variable in the PCC pavement family model. Terminal IRI (IRI_t which was the IRI just prior to a treatment) was also a significant predictor of IRI and was directly or indirectly included in the FDA and Comp family and treatment models. Additional significant IRI predictors (depending on the model) were the climate parameters DT32 (days/year that air temperature was below freezing), FT (freeze/thaw cycles per year), and DP01 (days/year that precipitation was at least 0.1-in.), subgrade soil parameters P200 (percent passing the #200 sieve) and Pclay (percent clay-size soil), and LstTrtThk (the last treatment thickness).

Although the literature indicated that traffic is a significant factor affecting treatment service life, neither Annual Average Daily Traffic (AADT) nor Annual Average Daily Truck Traffic (AADTT), both measured by direction of travel (one-way), showed significance as predictors on their own. Even accumulated traffic, the product of SA and AADT (or AADTT), seldom showed significance and/or possessed the expected sign on the regression coefficient.

Task 3: The research reported in this document was performed by researchers from Missouri S&T and UMC. The overall goal of Task 3: *Pavement Evaluation Tools – Data Collection Methods* was to conduct a literature search to identify and evaluate methods to rapidly obtain network-level and project-level information relevant to in situ pavement condition to enable pavement maintenance decisions. The focus of these efforts was to explore existing and new technologies that can be used to collect data and develop the knowledge, procedures, and techniques that will allow MoDOT to perform pavement evaluation. It was concluded that each of the recommended technologies could be utilized effectively by appropriately trained MoDOT personnel. The ultrasonic surface wave, impact echo, ground penetrating radar, and electrical resistivity tools are readily stored and can be transported to a work site in a pick-up truck. The falling weight deflectometer and rolling dynamic deflectometer require dedicated vehicles. The field data acquired using all eight technologies are readily processed using commercially-available software and a laptop or desktop computer. Only two of the eight recommended technologies (ground-coupled GPR and air-launched GPR) are compatible with the ARAN vehicle. Only air-launched GPR was recommended for network evaluation.

Task 4: The research reported in this document was performed by researchers from Missouri S&T and UMC. The overall objective of Task 4: *Site Specific Pavement Condition Assessment* was to thoroughly assess the cost-effectiveness and utility of selected non-invasive technologies as applicable to MoDOT roadways. Assessment of the *network*-applicable non-invasive imaging tools was based on the analyses of data acquired along two designated roadways, while assessment of the *project*-applicable non-invasive imaging tools was based on eight designated roadways. GPR (400 MHz) and air-launched GPR were used to acquire data along the two designated network-level roadways. Pavement cores extracted from each site served as ground truth for the non-invasive imaging technology results. It was concluded that air-launched GPR can be used for determination of bituminous layer thickness, debonding, stripping, and void detection. High-frequency ground-coupled GPR can be used for bituminous layer thickness, debonding, reinforcing mesh location, and void detection. Low-frequency ground-coupled GPR can be used for location of shallow utilities. Ultrasonic surface wave analysis can be used for bituminous layer thickness determination.

Task 5: This research was performed by researchers from Missouri S&T. The general objective of Task 5: *Pavement Treatment Trigger Tables/Decision Trees and Treatment Candidate Selection Process* was to provide a manual that MoDOT can use to select the most appropriate pavement treatment for a given roadway project. The selection procedure includes cost assessment methods. The input to the trigger tables entails such factors as an overall condition indicator (PASER), smoothness (IRI), individual distress types-extent-severity (e.g. thermal cracking, block cracking, fatigue cracking, longitudinal cold joint cracking, joint reflective cracking, longitudinal wheel path cracking, longitudinal edge breakup, patches and potholes, raveling, polishing, stable rutting, corrugations and shoving, bumps and sags, bleeding, D-cracking, pop-outs, spalling, corner cracks, faulting), pavement type, history of treatment, and some measure of traffic through the surrogate Surface Age.

Trigger table output is one or more potential appropriate treatments, which would consider pavement condition, traffic, climate (which affects construction timing and treatment performance), work zone duration (e.g. traffic control issues), time of year construction, construction quality risk, availability of quality contractors and quality materials, longevity of treatment, and availability of funding. Trigger tables include preservation treatments (chip seals, micro-surfacing, slurry seals, ultrathin bonded asphalt wearing surface (UBAWS), crack sealing, crack filling, thin overlays, milling and filling, profile milling, hot in-place recycling, cold in-place recycling, diamond grinding, whitetopping, load transfer retrofit and joint repair, and partial/ full depth repair.

Task 6: The research reported in this document was performed by researchers from UMC. The objective of this Task: *Re-Calibration of Triggers and Performance Models* was to develop the concept and framework for a procedure to routinely re-calibrate and update the Trigger Tables, Family models, and Treatment Performance Models, and to create Segment-specific deterioration curves, new Family models, and new Treatment Performance models. The report summarized the need for updating the models developed in Task 2 and used in Task 5. There were three Family models: Full-Depth Asphalt, Concrete, and Composite as well as three Treatment Performance models: 1-in. overlays on asphalt, chip seals on asphalt, and thin structural overlays on concrete. Recommendations for future enhancements of the required data were presented. The necessity for creation of new models was emphasized: Segment-specific models, new Family models, and additional Treatment Performance models, in terms of both IRI and PASER ratings. Updating the trigger tables (created in Task 5) was also discussed. Finally, a detailed list of obstacles to data mining and handling with possible solutions was offered.

Specific recommendations are delineated in each of the Task reports, contained in Volumes II through VII.

The benefits of the *Pavement Preservation Research* program (cost savings with respect to pavement maintenance and improved level of pavement performance ratings) will be sustainable only if the trigger tables, Family models, Segment-specific deterioration curves, Treatment Performance models, and the treatment selection methodology are re-calibrated and updated periodically. Failure to do so will ultimately lead to pavement management (preservation/rehabilitation) decisions being based on inadequate, outdated or even incorrect information. The data and information on which the pavement management process as delivered by the Pavement Preservation program are not static. They will continue to evolve in such areas as: technology, policies, desired sustainability level of pavements, and other contributing factors. For the program to have the maximum and sustainable benefit, periodic updating is required and will result in continual increasing accuracy of both pavement condition forecasts and refinement of the decisions among most appropriate (performance-wise and cost-wise) treatments for pavements under given conditions.

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