PAVEMENT PROGRAM PLANNING
BASED ON MULTI-YEAR COST-EFFECTIVENESS ANALYSIS

Prepared By
Fan Peng
Yanfeng Ouyang
University of Illinois at Urbana-Champaign

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Abstract
Many traditional planning procedures tend to postpone maintenance, repair, and rehabilitation (MR&R) work until the pavement facility becomes significantly deteriorated. Any repair and rehabilitation work carried out after significant deterioration of the pavement turns out to be time consuming and not cost effective. The Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) have been actively promoting preventive maintenance policies to state DOTs. Such proactive policies prescribe less-costly treatments for pavement facilities in order to prevent severe deterioration from occurring.

This research project aims to develop such a cost effective planning procedure for the State of Illinois. The objective of this study is to develop an advanced pavement program planning procedure based on multi-year cost-effectiveness analysis. As a part of this project, a study on existing successful pavement management programs was conducted to understand the state of practice. Effective (yet simple) mathematical models have been developed to support pavement program planning practices. The developed models incorporate the concept of cost effective ranking for pavement program planning and would help in making decisions that focus on preventive maintenance. A spreadsheet-based software has been developed to serve as a decision-making support tool that facilitates the planning process. This software will help IDOT officials to easily incorporate the developed mathematical ranking models into their routine pavement maintenance planning process. The outcomes of this project (planning models and decision-support software) will help IDOT staff (i) make better decisions on the cost-effectiveness of MR&R activities and (ii) facilitate cost effective highway preservation and improvement in Illinois.
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DISCLAIMER

The contents of this report reflect the view of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Illinois Center for Transportation, the Illinois Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.
EXECUTIVE SUMMARY

Many traditional planning procedures tend to postpone maintenance, repair, and rehabilitation (MR&R) work until the pavement becomes significantly deteriorated. Any repair and rehabilitation work that is carried out after significant deterioration of the pavement turns out to be time-consuming and cost-ineffective.

The Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) have been actively promoting preventive maintenance policies to state DOTs. Such policies prescribe less-costly treatments for pavement facilities in order to prevent severe deterioration from occurring. The basic idea is to consider both the long-term effectiveness and the costs of the candidate projects. Such approaches have been tested in several peer states (such as Arizona) and are proven to be significantly effective in saving capital investments over the long run.

This research project aims to develop such a cost-effective planning procedure for the State of Illinois. The objective of this study is to develop an advanced pavement program planning procedure based on multi-year cost-effectiveness analysis. As a part of this project, a study on existing successful pavement management programs was conducted to understand the state of practice. Effective (yet simple) mathematical models have been developed to support pavement program planning practices. The developed models incorporate the concept of cost-effective prioritization for pavement program planning and would help in making decisions that focus on preventive maintenance. Spreadsheet-based software has been developed to serve as a decision-making support tool that facilitates the planning process. This software will help IDOT officials easily incorporate the developed mathematical models into their routine pavement maintenance planning process. The outcomes of this project (planning models and decision-support software) will help IDOT staff make better decisions on the cost-effectiveness of MR&R activities and facilitate cost-effective highway preservation and improvement in Illinois.
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<td>AASHTO</td>
<td>American Association of State Highway and Transportation Officials</td>
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<td>AUC</td>
<td>Area Under the performance Curve</td>
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<td>ADOT</td>
<td>Arizona Department of Transportation</td>
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<td>AC</td>
<td>Asphalt Concrete</td>
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<tr>
<td>AADT</td>
<td>Average Annual Daily Traffic</td>
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<td>B/C</td>
<td>Benefit/Cost Ratio</td>
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<td>CPM</td>
<td>Capital Preventive Maintenance</td>
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<td>CRS</td>
<td>Condition Rating Survey</td>
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<td>CM</td>
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<td>DOT</td>
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<td>E/C</td>
<td>Effectiveness/Cost Ratio</td>
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<td>FHWA</td>
<td>Federal Highway Administration</td>
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<td>HDM</td>
<td>Highway Development and Management System</td>
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<td>HPMA</td>
<td>Highway Pavement Management Application</td>
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<td>ICT</td>
<td>Illinois Center for Transportation</td>
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<td>IDOT</td>
<td>Illinois Department of Transportation</td>
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<td>IBC</td>
<td>Incremental Benefit-Cost</td>
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<td>IRI</td>
<td>International Roughness Index</td>
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<td>KDOT</td>
<td>Kansas Department of Transportation</td>
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<td>LR</td>
<td>Lagrangian Relaxation</td>
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<td>LCC</td>
<td>Life-Cycle Cost</td>
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<td>LCCA</td>
<td>Life-Cycle Cost Analysis</td>
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<tr>
<td>MR&amp;R</td>
<td>Maintenance, Repair, and Rehabilitation</td>
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<td>MCE</td>
<td>Marginal Cost-Effectiveness</td>
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<td>MDOT</td>
<td>Michigan Department of Transportation</td>
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<td>MYP</td>
<td>Multi-Year Prioritization</td>
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<td>NCHRP</td>
<td>National Cooperative Highway Research Program</td>
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<td>NOS</td>
<td>Network Optimization System</td>
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<td>Overlays and Rehabilitation</td>
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<td>PDI</td>
<td>Pavement Distress Index</td>
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<td>PSC</td>
<td>Pavement Structural Condition</td>
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<td>PCC</td>
<td>Portland Cement Concrete</td>
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<td>PM</td>
<td>Preventative Maintenance</td>
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<td>PPS</td>
<td>Program Planning System</td>
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<td>RM</td>
<td>Reactive Maintenance</td>
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<td>Rehab</td>
<td>Rehabilitation</td>
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<tr>
<td>R&amp;R</td>
<td>Rehabilitation and Reconstruction Maintenance</td>
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<tr>
<td>RSL</td>
<td>Remaining Service Life</td>
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<td>RQFS</td>
<td>Road Quality Forecasting System</td>
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<td>RM</td>
<td>Routine Maintenance</td>
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<td>WSDOT</td>
<td>Washington Department of Transportation</td>
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<td>WSPMS</td>
<td>Washington Pavement Management System</td>
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<td>WBRP</td>
<td>Weighted Benefit Ranking Procedure</td>
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CHAPTER 1 INTRODUCTION

Regular and effective maintenance is required to keep the existing road infrastructure operating at a satisfactory level of service. The state Departments of Transportation (DOT) usually have a pavement management policy to make pavement program planning decisions. Conventionally, the allocation of available funds is prioritized based on the potential benefits from improving pavement conditions; i.e., changes in pavement condition indices. However, as poorer pavements tend to have larger potential for improvement, the conventional ranking procedure always gives high priority to pavements in poorer condition. It tends to postpone maintenance, repair, and rehabilitation (MR&R) work until the pavement becomes significantly deteriorated. By then, time-consuming and cost-ineffective projects have to be carried out to recover pavement conditions.

Any efforts to repair and rehabilitate pavements that have deteriorated beyond a certain extent have proved to be costly and time-consuming. Hence, a preventive maintenance system considering project cost-effectiveness would be a more effective option than the conventional method of improving the pavement in the poorest condition. The Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) have been actively promoting preventive maintenance policies to state DOTs. Such proactive policies prescribe less-costly treatments for pavement facilities in order to prevent severe deterioration from occurring. The policies help avoid costly, time-consuming MR&R activities and the associated major traffic disruptions.

Comprehensive cost-effectiveness analyses for pavement MR&R have been implemented in several states (such as Arizona), and are proven to be more cost-effective than the “worst first” planning approach. The basic idea is to consider not only effectiveness (in terms of CRS, IRI and rutting depth changes), but also costs of the candidate projects. Very often, preventive pavement maintenance policies will turn out to be preferable in terms of effectiveness/cost ratio. Such approaches are effective in saving capital investments over the long run.

The objective of this study is to develop an advanced pavement program planning procedure based on multi-year cost-effectiveness analysis. As a part of this project, a study on existing successful pavement management programs was conducted to understand the state of practice. Effective (yet simple) mathematical models have been developed to support pavement program planning practices. Spreadsheet software has been developed to serve as a decision-making support tool that facilitates the planning process.

The product of this project (planning model and software) will help IDOT staff (i) make better decisions on the cost-effectiveness of MR&R activities and (ii) facilitate highway preservation and improvement in Illinois. This report explains the background with which the software was developed and describes its functionalities. This report is also expected to serve as a user’s manual to the staff of IDOT.

The remainder of this report is organized as follows: Chapter 2 provides a comprehensive literature review and the practice at leading states; Chapter 3 discusses the technical background and existing methodologies; Chapter 4 explains the detailed functionalities of the software; Chapter 5 discusses possible future work.
CHAPTER 2 LITERATURE REVIEW

This section reviews various current analysis approaches and practice for pavement management in the United States. Pavement-management-related technical reports (e.g. FHWA, AASHTO and NCHRP publications) were reviewed to study pavement maintenance policy. Information on successful pavement management programs in some states, such as Arizona and Washington, were collected and summarized.

2.1 PAVEMENT MANAGEMENT SYSTEM (PMS) OVERVIEW

The objective of this project is to develop an advanced pavement program planning procedure based on multi-year cost-effectiveness analysis for IDOT. Such a planning procedure is usually conducted in six steps:

- Determine pavement condition indices (PCI)
- Develop prediction model
- Define treatments
- Build decision tree
- Determine criteria
- Develop prioritization approach

The following subsections section briefly reviews these steps.

2.1.1 Pavement Condition Indices

The most commonly used pavement condition indices include Distress, Rutting, and Roughness. The indices for distress are of various types, such as Condition Rating Survey (CRS, used by IDOT), Pavement Distress Index (PDI, used by the Arizona DOT), and Pavement Structural Condition (PSC, used by the Washington DOT), and are acquired from different measurement processes. Adopting different indices may lead to different pavement management analysis results.

2.1.2 Prediction Model

Linear and polynomial deterministic prediction models are adopted by many agencies to predict the pavement performance over time:

\[
PCI = PCI_{\text{max}} - b \times Age
\]

\[
PCI = PCI_{\text{max}} - b \times Age^m
\]

where \( b \) and \( m \) are regression parameters.

The form of prediction model depends on the type of PCI. For example, IDOT uses a linear IRI prediction model with the International Roughness Index (IRI) as the roughness measure; the Arizona DOT (ADOT) uses a sigmoid PSR prediction model with Pavement Serviceability Rating (PSR) as the roughness measure. PSR is known to be related to IRI as follows:

\[
PSR = 5 \times e^{-0.0038 \times IRI}
\]

The parameters of the prediction models are normally obtained via regression, for different types of pavements. Pavement types are often classified by characteristics such as structural design (e.g. Portland cement concrete or asphalt concrete) and roadway functional class (e.g. interstate or other marked routes). Some agencies also consider the last
maintenance treatment as a characteristic for pavement type definition. In that case the parameters of the performance curve will depend on the last treatment (e.g. SMART projects usually have shorter life spans than standard projects).

2.1.3 Treatment Definition

Cost and effectiveness are usually defined for every treatment type or maintenance project. Generally, cost may include agency costs (i.e. maintenance cost) and user costs (e.g. work zone costs caused by traffic diversion and normal operation costs caused by roughness). Effectiveness may be measured in different ways, such as increased remaining service life (RSL), increased PCI (increase to a value or by a value), or increased area under the performance curve (AUC). Some of the effectiveness measures are shown in Figure 1.

![Figure 1. Popular effectiveness measurement of pavement treatments.](image)

Treatments are usually classified into several categories, such as Routine or Corrective Maintenance (CM), Preventative Maintenance (PM), and Rehabilitation and Reconstruction Maintenance (R&R) (Zaghloul et al. 2006; MnDOT 2007). CM, such as pothole patching, is a temporary maintenance which is generally not costly, but has very limited effect on a pavement’s future performance. CM is used to keep poor condition pavements temporarily usable when there are not enough funds for R&R. PM, such as thin asphalt overlay, is less costly than R&R, but can only be used on pavements in rather good conditions. R&R is applied to poor pavements, and is very costly. Some treatments, such as crack sealing, may be counted as either CM or PM, depending on the conditions of the pavement where they are applied.

Some agencies only consider treatment types in analysis at the pavement network level; they determine the specific treatments for sections at the individual pavement project level. Some other agencies have detailed project-treatment lists in the network-level analysis.

2.1.4 Decision Tree

The decision tree recommends one or several alternative strategies for every roadway section, based on the conditions of the section (such as pavement type, age and current PCI). A strategy is the schedule for a set of treatments. If the strategy contains only one treatment, it is called ‘single treatment strategy’, or usually “project”; otherwise it is called “multiple treatment strategy”, as shown in Figure 2. If more than one strategy is proposed for a roadway section, only one of them will be chosen.
2.1.5 Project Prioritization Criteria

Criteria are used to measure the values of the pavement strategies (or projects), to compare them, and to determine which ones will be performed. Criteria are generally expressed in terms of benefits and effectiveness. The difference between them is that benefits, such as salvage value and reduced user costs, are represented by monetary units; while effectiveness, such as AUC and PCI, are represented by non-monetary units. Costs can be considered as negative benefits, so Life-Cycle Cost (LCC) is a type of benefit criteria. Different effectiveness criteria can be combined together or converted to benefits (e.g., safety effectiveness is usually converted to benefit for LCC analysis) by defining a weight function. They can also be used separately to define multiple constraints or objective functions. Benefits (costs) and effectiveness shall be defined for every strategy in pavement management analysis.

Effectiveness is usually calculated based on factors such as PCI, AUC, and RSL. If PCI or AUC is included in the calculation of the benefit/effectiveness, there is an assumption that equal increments of PCI always yield equal benefit/effectiveness. For example, the effectiveness that PCI increases from 20 to 40 should be equal to the effectiveness from 80 to 100. This assumption is not always realistic. Therefore, some types of PCI may not be suited for certain types of effectiveness evaluation.

Benefit is usually calculated by factors such as agency costs (e.g. construction cost, maintenance cost and salvage value) and user costs (e.g. work zone cost, normal operation cost and crash cost).

Because maintenance costs are needed to formulate the budget constraint, they are almost always defined for strategies, even though they are not included in the benefits. Salvage value is the sum of RSL at the end of the analysis period and the residual value. The residual value part may be positive or negative, but it is usually negligible when discounted over a long analysis period. The RSL part depends on the prediction curve. FHWA (1998) provides a method to calculate the monetary value of RSL:

\[
\text{Benefit} = \text{Cost of the Last Treatment} \times \frac{\text{RSL at the End of the Analysis Period}}{\text{Increased RSL due to the Last Treatment}}.
\]
This method converts the effectiveness of RSL to benefits. However, according to this formula, a treatment with high cost but low effectiveness may yield high benefit (because the benefit is proportional to the cost of the treatment). So this formula should be used with caution.

User costs are not easy to estimate, because more information is required about the strategies. For example, in order to calculate crash cost (or safety benefit), crash rates before treatment should be available and those after treatment should be estimated. The FHWA (1998) provides some methods to calculate user costs.

LCC is a commonly used benefit criterion. The FHWA (1996) recommends an analysis period of at least 35 years for LCC analysis (LCCA). In such a long period, more than one treatment is usually applied to the sections, so multiple treatment strategies should be considered. However, such strategies are difficult to implement in the context of network-level analysis. LCCA also usually considers more detailed factors (such as user costs) and requires more input information, which may not be readily available. So LCCA is often used only at the individual project-level.

Benefit/Cost (B/C) ratios and Effectiveness/Cost (E/C) ratios are also used as plausible criteria. FHWA (1998) suggests that B/C ratios not be used because it is difficult to distinguish benefits from costs. For example, salvage value can be either counted as benefit, or be multiplied by -1 and counted as part of the agency costs. AADT and the length of the pavement section may be included in the benefit/effectiveness formula to compute the total benefit/effectiveness received by all vehicles on the whole section. Discount rate can be used to convert future benefits/effectiveness and costs to their present values.

As a final remark, different criteria may be used to determine a set of candidate plans. The best plan will help determine the most appropriate criteria.

2.1.6 Prioritization

Three categories of methods can be used to prioritize alternative strategies and candidate sections: ranking, heuristic prioritization, and optimization.

Ranking is the simplest approach. The strategies are ranked by certain criteria such as the E/C ratios, and then those projects with the top criteria values are selected from the list until the budget is exhausted.

Heuristic prioritization includes the marginal cost-effectiveness (MCE) analysis (adopted by the Minnesota Department of Transportation) and the incremental benefit-cost (IBC) analysis (adopted by the Indiana Department of Transportation), and is usually able to yield near-optimum solutions.

The MCE approach calculates MCE for every project at the beginning of a series of rounds. Then in each round, it uses the strategy with the highest MCE (suppose this strategy is for pavement section A) to replace the current selected strategy (do-nothing is counted as a default strategy if no strategy is ever selected) for section A, and recalculates the MCE of other unselected strategies for section A as:

\[ MCE_i = \frac{E_i - E_s}{C_i - C_s}, \]

where \( E_i \) and \( C_i \) are the effectiveness and cost of any strategy \( i \), and \( E_s \) and \( C_s \) are those of the current selected strategy. The following table gives a simple example of this method.
Table 1. Example of the MCE approach.

The IBC (effectiveness can also be used instead of benefit) approach first ranks the strategies by cost within every pavement section, and calculates their IBC as follows:

\[
IBC_i = \frac{B_i - B_{i-1}}{C_i - C_{i-1}},
\]

where \(B_i\) and \(C_i\) are the benefit (or effectiveness) and cost of strategy \(i\) (i.e., strategy with the \(i\)-th lowest cost in the section). Then it puts the strategies of all sections together, and re-ranks them by IBC. In each round, it uses the strategy with the highest IBC (suppose this strategy is for section A) to replace the current selected strategy for section A, just as the MCE approach does. However, unlike MCE approach, it does not re-calculate IBC in each round. Table 2 shows a simple example.

Table 2. Example of the IBC approach.

The IBC method requires that strategies with higher cost must have higher benefit and lower IBC (i.e. follow the law of diminishing returns) in every section. MCE does not have such requirement. Though IBC and MCE methods use B/C ratios or E/C ratios, they are actually using benefit or effectiveness criteria but not B/C ratio or E/C ratio criteria. The treatment costs are only utilized in budget constraints but not in the objective functions or benefit calculations.

If the pavement program planning is conducted for multiple years with a single treatment strategy (or project), there are two alternative ways to implement multi-year prioritization (MYP): (i) prioritize for each year separately; and (ii) prioritize for all years simultaneously. With the first option, prioritization is repeated for each consecutive year. With the second option, projects in different years are put together for prioritization, just as if all projects were in a single year. However, there are multiple budget constraints, and when a project is selected, the cost contributes to the total cost in that corresponding year.

6
If there are multiple treatment strategies, the problem is much more complex: the
criterion of a treatment is related to all other treatments conducted in other years, but the
prioritization process requires a pre-calculated fixed criterion.

Optimization is quite complex and is often the most time-consuming. But it has the
advantage of producing the most optimal decision. For example, a network optimization system
(NOS) using Dantzig-Wolfe Decomposition is adopted by the Department of Transportation in
Arizona, Kansas, and Alaska. A detailed description can be found in Alviti, et al. (1997).

2.2 EXISTING PAVEMENT MANAGEMENT SYSTEMS (PMS)

This section reviews current PMS approaches in several states.

2.2.1 Arizona
The Arizona Department of Transportation (ADOT) uses Highway Pavement
Management Application (HPMA) developed by Stantec Inc. as its PMS tool. In HPMA,
Pavement Serviceability Rating (PSR) and Pavement Distress Index (PDI) are used to measure
pavement conditions. PSR is calculated based on IRI; PDI is calculated based on indices such
as cracking, rutting, flushing and patching (Zaghloul et al. 2006).

The prediction models for PSR and percentage cracking are as follows:

\[ PSR = PSR_{\text{max}} - e^{A - B \times C \times \text{Age}} \]

Percentage Cracking = \[ e^{-k \times \text{Age}} \]

where \( A, B, C, k \) and \( m \) are regression parameters.

HPMA defines impact models for about 80 treatments. The impact includes jump
(increase in the pavement condition), holding period (where the pavement condition is held
constant), and a new performance curve.

HPMA classifies its maintenance program into three classes: Corrective Maintenance
(CM), Preventive Maintenance (PM) and Rehabilitation (Rehab). All sections whose age is more
than 7 years go through the appropriate CM decision tree. Other sections go through the PM
decision tree and HPMA selects the most cost-effective PM program by the first optimization.
Then all sections go through the Rehab decision tree and HPMA selects the most cost-effective
Rehab program by the second optimization. The optimization is based on the cost-effectiveness
analysis. The effectiveness is calculated as:

\[ \text{Effectiveness} = f(\text{AADT}) \times \text{SectionSurfaceArea} \times \text{AUC} \]

2.2.2 Washington
The Washington Department of Transportation (WSDOT) uses WSPMS as the primary
PMS tool, and the Highway Development and Management System (HDM-4), which is
developed by the World Bank, as a supplement.

Pavement Structural Condition (PSC), Pavement Rutting Condition (PRC) and Pavement Profile
Condition (PPC) are used as measures of pavement conditions. The prediction model for PSC
is as follows (Broten 1996):

\[ PSC = 100 - m \times \text{Age}^p \]
where \( m \) and \( P \) are regression parameters. Prediction curve are developed for every pavement type, and also for individual sections if possible.

Treatments are classified into four levels: Routine Maintenance (RM), Preventative Maintenance (PM), Overlays and Rehabilitation (OVR), and Reconstruction. LCCA is used to select candidate programs.

### 2.2.3 Michigan

The Michigan Department of Transportation (MDOT) uses RSL as the measure of current pavement conditions. Pavements are classified based on RSL into six categories, from I to VI. For example, category I pavements have the RSL of 0–2 years and category VI pavements have the RSL of 23–25 years.

MDOT uses the Road Quality Forecasting System (RQFS) to predict the future condition of pavement. Maintenance treatments are classified into three types: Reconstruction and Rehabilitation (R&R), Capital Preventive Maintenance (CPM) and Reactive Maintenance (RM).

R&R is applied to category I pavements. CPM is applied to category II, III, IV or V pavements and increases their categories by one or two. RM is used to keep a poor pavement safe until R&R is possible.

### 2.2.4 Kansas

The Kansas Department of Transportation (KDOT) adopts a three-tier prioritization method, using worst-first ranking approach to select major R&R projects, network optimization approach (NOS) to select minor rehabilitation projects and a routine maintenance strategy to determine CM and PM projects.
CHAPTER 3 PAVEMENT PROJECT PLANNING

3.1 CURRENT ILLINOIS PRACTICE

The Illinois Department of Transportation (IDOT) uses a mainframe database, Illinois Roadway Information System (IRIS), to store roadway network information. IDOT uses another mainframe database, Program Planning System (PPS), to store candidate multi-year highway improvement projects information. Several spreadsheet applications are used to help prioritize and select projects based on the factors of CRS, AADT and the functional importance of the highway.

The candidate projects are submitted by nine districts every year. The districts are given a funding allocation for each fiscal year of the program. Projects and necessary pre-construction activities (e.g. preliminary engineering, land acquisition, utility adjustments) are identified and accounted for these allocations. IDOT provides each district with figures of bridge and mileage that are necessary to meet statewide system/strategic performance goals over the multiyear program period. The districts identify projects and attempt to both meet the condition goals and stay within their funding allocations. Bridge system condition has a higher priority than mileage. Large congestion mitigation projects and new expansion projects are added only at the direction of IDOT top management.

The projects are proposed to be accomplished in the next six years. The estimated cost of each project is reported but the benefit/effectiveness is not estimated by the districts. Some districts develop priorities for the projects, but their analytical methods are different and their priority indices are not consistent. The districts may investigate several alternative treatments for one section.

The central office reviews these candidate projects and finally selects about 7,000 to 8,000 projects to be included in the Proposed Multi-Year Highway Improvement Program (MYP). The MYP is updated every year, and the program for the first year in the MYP becomes the highway program for the current fiscal year.

IDOT uses CRS as the measure of pavement conditions. About 10,000 miles of highways are surveyed every year, so every mile of pavement is surveyed every other year. Half of the CRS values are observed in the current year and half are predicted based on the last year’s values. The prediction models for CRS are piecewise linear. Recent research (Heckel and Ouyang 2007) has created or revised the models for 28 pavement types. The influences of D-cracking and SMART (thin overlays) on pavements have also been considered in the models.

The CRS value assigned to a pavement section, together with the AADT a roadway carries and its functional importance is used to prioritize roadway deficiencies. The categories and definitions for pavement needs are:

- Needs Improvement (Backlog) – condition has deteriorated to the level where an improvement is recommended now. If the improvement is delayed, the ultimate cost could be much higher.
- Acceptable (Accruing and Adequate) – A pavement that is not in need of an immediate improvement. Accruing pavements are those that will deteriorate to a backlog condition over the next five years. Adequate pavements need little to no improvements and will not deteriorate to backlog within the next five years.

The goal of IDOT is to keep the miles of highways that meet the backlog criteria less than 10 percent of the state highway system.
PPS defines each improvement type in an improvement type list, including pavement improvements such as Patching, Resurfacing (3R), Resurfacing (3P) and Reconstruction. However, pavement improvements are only a part of improvement types. There are also bridge improvements, railroad improvements, intersection improvements and so on. Neither cost nor effectiveness is defined for these improvement types.

The following two modules are developed to further improve the Illinois pavement planning program: pavement project effectiveness calculation and project prioritization methodology.

3.2 MODULE 1: PROJECT EFFECTIVENESS CALCULATION

3.2.1 Pavement Condition Indices

CRS data for roadway sections are available in IDOT’s database. If data for other PCI such as IRI and rutting are provided, they can also be used to calculation effectiveness combined with CRS.

3.2.2 Prediction Model

Piecewise linear models recently developed for Illinois (Heckel and Ouyang 2007) in FHWA-ICT-07-012 are used to predict the conditions of the pavements in the future. These models were created for 28 pavement types. Special cases such as D-cracking and SMART treatment were considered in the models.

3.2.3 Treatment Definition

Costs are defined for every project in IDOT’s database. The maximum improved CRS can be defined by treatment type in the program’s database. Based on these data and the prediction models, increased AUC, increased RSL and increased PCI are calculated as effectiveness measurements.

3.3 MODULE 2: PROJECT PRIORITIZATION

3.3.1 Decision Tree

Because the projects have already been decided by districts before prioritization, the decision tree does not need to be implemented in the program.

3.3.2 Criteria

Increased AUC, increased RSL, and increased PCI are multiplied by AADT and road length to compute the total effectiveness received by all traveling vehicles. We assume a project covers all lanes and the whole length of the road, because whether the whole or only part of the section is improved is not defined in the database. However, it should be noted that if only part of the section is improved, the actual effectiveness is also part of the calculated effectiveness. An “effectiveness per capita” option is provided. The effectiveness per capita is calculated by dividing total effectiveness by the population of the roadway section’s county. This index can be considered as the average effectiveness that a local resident receives. E/C ratio is then calculated for the selected type of effectiveness measure. Because each fiscal year has its own budget, and the budget is only allowed to be allocated to the projects in that year, the discount rate does not need to be considered in the analysis.

3.3.3 Prioritization

Our program provides three basic prioritization methods for the six-year planning at IDOT: (i) ranking for all years, (ii) IBC for all years simultaneously, and (iii) IBC for each year separately.
In addition, the Lagrangian Relaxation (LR) method is used to obtain the optimality gap of the solution (i.e., an index to the quality of the solution; a small gap indicates a better solution) and to further optimize the solution. Appendix A provides the mathematical model and solution approach based on LR.

To illustrate the difference of the prioritization methods, our program was tested with an example with 1000 sections and 3000 projects. The initial CRS and the project costs were randomly generated. The data does not meet the requirement of the IBC method that alternatives follow the law of diminishing returns (this requirement may not be met by real data either), so all projects violating this law are not considered. The solution obtained by the ranking method is further optimized using LR (using only several seconds of computation time). The result of this example is shown in the table below.

<table>
<thead>
<tr>
<th>Method</th>
<th>Sum of Effectiveness</th>
<th>Sum of Cost</th>
<th>Average Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranking</td>
<td>320897</td>
<td>$8,074,000</td>
<td>7.28%</td>
</tr>
<tr>
<td>IBC for All Years</td>
<td>320714</td>
<td>$8,139,000</td>
<td>2.47%</td>
</tr>
<tr>
<td>IBC for Each Year</td>
<td>320200</td>
<td>$8,168,000</td>
<td>7.07%</td>
</tr>
<tr>
<td>LR</td>
<td>321430</td>
<td>$8,040,000</td>
<td>2.30%</td>
</tr>
</tbody>
</table>

Table 3. Comparison of different methods for the test example.

It can be seen that the simple ranking method can produce a rather good solution.

3.4 SOFTWARE SETUP AND ISSUES

The pavement program software was developed and tested with Microsoft Office Excel 2003 and Microsoft Visual Basic 6.5 (embedded in Office Excel 2003), on the Microsoft Windows XP Professional operating system. It is also expected to run on any Microsoft Windows operating system with Office Excel 2003 or higher version. At this point, the software does not work on any Macintosh OS version with Office 2008 because Visual Basic support is not available in Microsoft Office for Macintosh 2008.

All .xls files (input file and software file) should be extracted from the ZIP compression package into the same folder (anywhere in the computer). Open “calculation.xls” to run the software.

Macros must be enabled in Excel. For Excel 2003, if the security level of Excel is “Medium”, Excel will show a security warning when opening the file. Click the "Enable Macros" button to enable macros. If the security level of Excel 2003 is “High”, user needs to change the security level to “Medium”. Open Excel 2003, select “Tools” menu, select “Macro”, and then “Security”. In the “Security” dialog box, select “Medium”, and click “OK”.

Sometimes, the user may receive an error message “Compile Error: Can't find project or library” when running the software. This is a common issue with Excel VBA. To solve this problem, follow these steps:

1. Make sure Excel is open.
2. Open the Visual Basic window by pressing Alt+F11, or select “Tools” menu, “Macro”, “Visual Basic Editor”. The Visual Basic window may have been opened automatically when the user receives the error message.
3. In the “Visual Basic” window, select “Tools”, “References”. If “References” option is grey (disabled), select “Run”, “Reset” first to stop the program from running.
4. In the “References” dialog box, uncheck all checkboxes marked with “MISSING: <referencename>.” Press “OK” button to close the dialog box.

5. Run the program again.

More information about this Excel problem can be found in the Microsoft Help and Support Webpage: http://support.microsoft.com/kb/283806/en-us.
CHAPTER 4 SOFTWARE FUNCTIONALITY

This section describes main features of the pavement planning program for the ICT Project R27-34. The software is developed based on the work plan and the communication with IDOT experts. Screenshots of various components are included for better illustration. The software consists of three parts, namely:

- User interface and VBA software
- Input files
- Output files

Figure 3 shows an overview of the program.

The following subsections briefly describe the software modules.

4.1 USER INTERFACE

The spreadsheet program is coded in “Calculation.xls.” The user interface consists of a set of “Radio buttons” and “Check boxes.” Users can select the options and click the ‘start’ button to start the calculation.

4.1.1 Effectiveness Measurement

The basic functionality of the software is to calculate the effectiveness of projects. See the left side of Figure 4. Users may select among different effectiveness measurements to
determine the formula for effectiveness calculation. The effectiveness measurements may be one of the following:
- Area under the curve
- Prolonged remaining life
- Improved CRS

If the “Effectiveness per Capita” check box is selected, E/C ratios will be calculated based on the effectiveness per capita values; otherwise they are calculated based on the total effectiveness value.

The software also predicts the change of CRS for every roadway section in the next five years.

4.1.2 Prioritization
An optional functionality of the software is to perform project prioritization; see the right side of Figure 4. When this option is selected, the program will recommend a set of projects, to which the treatments should be applied, based on the calculation of the effectiveness. Users may choose among several prioritization methods. If “Further Optimization” is checked, the program will produce a better solution from the advanced LR algorithm.

Once the desired options are selected and the ‘start” button is clicked, the software will run and generate the output file “Result.xls”.

Figure 4. Screenshot of “Calculation.xls” – User Interface.
4.2 OUTPUT FILE – “RESULT.XLS”

The “Result.xls” file is the output of the software and it contains three worksheets.

4.2.1 “Project” Sheet

The “Project” sheet (Figure 5) lists all the projects along with the computed effectiveness. Users may rank and compare the projects by cost, effectiveness or E/C ratio. If the “Prioritization” box is checked, the recommended v.s. not recommended projects are highlighted in different colors. A detailed explanation of the columns in this worksheet is as follows:

- **“ID”** - Project ID number as defined in PPS database.
- **“District”** - District of the project.
- **“Roadway”** – Name of the roadway section.
- **“Type”** - Pavement improvement type, such as patching, overlays or reconstruction. Types and codes are defined in IDOT’s database.
- **“Year”** – Fiscal year when the project is completed.
- **“Cost”** - Project cost.
- **“Total Effectiveness”** – Effectiveness received by all vehicles. Proportional to AADT and section length.
- **“Effectiveness per capita”** – Average effectiveness received by local residents. Calculated by dividing total effectiveness by county population.
- **“E/C ratio”** – Effectiveness (total or per capita, depending on if the user selected the “effectiveness per capita” option) divided by cost.
- **“Recommend”** – This column only exists when “prioritization” option is selected. “Y” means the project is recommended; “N” otherwise.

![Figure 5. Screenshot of “Result.xls” – “Project” Worksheet](image)

4.2.2 “Statistics” Sheet

The “Statistics” sheet (Figure 6) lists the sum of costs, effectiveness and backlogs for every district in every year. These values should satisfy the budget constraints defined in Constraint.xls. This sheet contains three tables, “Cost” table, “Effectiveness” table and “Backlog”
The effectiveness may be either total effectiveness or effectiveness per capita depending on the user’s choice.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2008</td>
<td>2009</td>
<td>2010</td>
<td>2011</td>
<td>2012</td>
<td>2013</td>
<td>Total</td>
</tr>
<tr>
<td>2</td>
<td>0.7472</td>
<td>0.7368</td>
<td>0.6912</td>
<td>0.5910</td>
<td>0.4978</td>
<td>0.4145</td>
<td>0.6471</td>
</tr>
<tr>
<td>3</td>
<td>0.3000</td>
<td>0.2500</td>
<td>0.2000</td>
<td>0.1500</td>
<td>0.1000</td>
<td>0.0500</td>
<td>0.3000</td>
</tr>
<tr>
<td>4</td>
<td>0.2503</td>
<td>0.1905</td>
<td>0.1307</td>
<td>0.0809</td>
<td>0.0306</td>
<td>0.0000</td>
<td>0.2503</td>
</tr>
<tr>
<td>5</td>
<td>0.6067</td>
<td>0.4772</td>
<td>0.3510</td>
<td>0.2541</td>
<td>0.1622</td>
<td>0.1106</td>
<td>0.4006</td>
</tr>
<tr>
<td>6</td>
<td>0.3000</td>
<td>0.2500</td>
<td>0.2000</td>
<td>0.1500</td>
<td>0.1000</td>
<td>0.0500</td>
<td>0.3000</td>
</tr>
<tr>
<td>7</td>
<td>0.4000</td>
<td>0.3300</td>
<td>0.2600</td>
<td>0.1900</td>
<td>0.1200</td>
<td>0.0600</td>
<td>0.4000</td>
</tr>
<tr>
<td>8</td>
<td>0.2000</td>
<td>0.1500</td>
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<td>0.0500</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.2000</td>
</tr>
<tr>
<td>9</td>
<td>0.5000</td>
<td>0.4000</td>
<td>0.3000</td>
<td>0.2000</td>
<td>0.1000</td>
<td>0.0500</td>
<td>0.5000</td>
</tr>
<tr>
<td>10</td>
<td>0.3000</td>
<td>0.2500</td>
<td>0.2000</td>
<td>0.1500</td>
<td>0.1000</td>
<td>0.0500</td>
<td>0.3000</td>
</tr>
<tr>
<td>11</td>
<td>0.2000</td>
<td>0.1500</td>
<td>0.1000</td>
<td>0.0500</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.2000</td>
</tr>
<tr>
<td>12</td>
<td>0.6000</td>
<td>0.4800</td>
<td>0.3600</td>
<td>0.2400</td>
<td>0.1200</td>
<td>0.0600</td>
<td>0.6000</td>
</tr>
<tr>
<td>13</td>
<td>0.3000</td>
<td>0.2400</td>
<td>0.1800</td>
<td>0.1200</td>
<td>0.0600</td>
<td>0.0300</td>
<td>0.3000</td>
</tr>
</tbody>
</table>

4.2.3 “CRS” Sheet

The “CRS” sheet lists the predicted CRS for each pavement section in each year under different projects (including do-nothing alternative). A detailed explanation of the columns in this worksheet is as follows:

- “Roadway” – Roadway section name.
- “District” – District of the roadway.
- “Project” – Project ID number. “0” for do-nothing alternative.
- “20xx” – Predicted CRS in that year. The first year is defined in “config.xls”.
- “Recommend” – This column only exists when the “Prioritization” option is selected. “Y” means the project is recommended; “N” otherwise.
4.3 INPUT FILES

The software requires a set of input files, which include information about roadways, projects, treatments and constraints. There are basically four input files (in Microsoft Excel format). Each of them is explained below.

4.3.1 Config.xls

This file contains the basic configuration information, as shown in Figure 8. Screenshot of “Config.xls” – input file. A detailed explanation of the columns in this file is as follows:

- “Current Year” – The first year of six fiscal years.
- “Backlog CRS” – Roadway sections with the CRS below this value are considered as backlog.
- “Minimum Allowed CRS” – If the CRS of a roadway section drops below this value, the section is considered as unusable. Some effectiveness measurements (AUC and RSL) are calculated based on this value.
- “Input/Output Files” – The file names of other input/output files.
4.3.2 ProjectList.xls

As shown in Figure 9, this file contains project information and roadway information, including project ID, roadway name, surface type, improvement type, and so on. These data can be obtained from IDOT’s PPS database. A detailed explanation of the columns in this file is as follows:

- “ID” – Project ID number as defined in PPS database.
- “Roadway” – Roadway section name.
- “District” – District of the project.
- “County” – County of the project.
- “Functional Class” – Class of the roadway, may be “interstate” or “others”.
- “Surface Type” – IRIS Surface Codes.
- “CRS” – CRS value of the roadway section.
- “CRS Year” – The year in which the CRS value was measured.
- “AADT” – Average Annual Daily Traffic of the section.
- “Length” – Length of the repaired section.
- “Improvement Type” – Pavement treatment type, such as patching, overlays or reconstruction. Types and codes are defined in PPS database.
- “Fiscal Year” – The fiscal year when the project is completed.
- “Alternative” – Whether this project is an alternative of another project. For example, if project B is an alternative of project A, B will have A’s project ID as its “Alternative” value. If B is not an alternative of any project, the value of this field will be zero. There can be more than one alternative for project A. In that case, those alternative projects B, C, D, ... should all be in the same roadway section as A, and their “Alternative” value should all be A’s ID. The program will recommend one of the multiple alternatives to be performed. This column is only used when the “Prioritization” option is selected.
4.3.3 PCI_Prediction.xls

This file contains several worksheets for a set of CRS prediction models, which are based on the recent IDOT pavement prediction project (Heckel and Ouyang 2007). A detailed explanation of the columns is as follows:

- **"Type"** – Codes of the IRIS Surface Types
- **"District"** – District which the roadway section belongs to.
- **"Standard"** – Model for standard pavement.
- **"D-Cracking"** – Model for D-cracked pavement (because whether a roadway section is D-cracked is not defined in the PPS database, this model is not used currently).
- **"SMART"** – Model for SMART pavement (Whether a roadway section had SMART treatment before is also not defined in the PPS database, so the program uses standard model for all sections as default. However, if a SMART project is applied during the six-year analysis, the program will use SMART model to predict the performance of that section in the future years).

The columns in the other worksheets of this file are similar except that the "SMART" column is not included in the "Interstate concrete" and the "Other concrete" worksheets.
4.3.4 Treatment.xls

This file defines the CRS improvement for each treatment type. For example, if “Patching” can increase the CRS of the pavement by 1.0, it will have “1.0” in “CRS Improvement” column. If a treatment type always raises the CRS to 9.0, it will have “9.0” in this column. The user can change these values and add new treatment types.

<table>
<thead>
<tr>
<th></th>
<th>A Code</th>
<th>B CRS Improvement</th>
<th>C Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>121</td>
<td>1.0</td>
<td>Patching</td>
</tr>
<tr>
<td>2</td>
<td>128</td>
<td>2.0</td>
<td>Reconstruction</td>
</tr>
<tr>
<td>3</td>
<td>130</td>
<td>3.7</td>
<td>Resurfacing (3R)</td>
</tr>
<tr>
<td>4</td>
<td>131</td>
<td>4.0</td>
<td>Resurfacing (3P)</td>
</tr>
<tr>
<td>5</td>
<td>142</td>
<td>5.2</td>
<td>Resurfacing (INT-1ST)</td>
</tr>
<tr>
<td>6</td>
<td>153</td>
<td>5.3</td>
<td>Resurfacing (INT-2ND)</td>
</tr>
<tr>
<td>7</td>
<td>163</td>
<td>5.0</td>
<td>Resurfacing (INT-3RD)</td>
</tr>
<tr>
<td>8</td>
<td>169</td>
<td>2.3</td>
<td>Resurfacing (SMART)</td>
</tr>
<tr>
<td>9</td>
<td>175</td>
<td>5.5</td>
<td>Resurfacing (INT-4TH)</td>
</tr>
</tbody>
</table>

Figure 11. Screenshot of “Treatment.xls” – Input File.

4.3.5 County.xls

This file contains the information of the population for counties of Illinois. This information is used to calculate the effectiveness per capita.

<table>
<thead>
<tr>
<th></th>
<th>A Name</th>
<th>B Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Adams</td>
<td>67046</td>
</tr>
<tr>
<td>2</td>
<td>Alexander</td>
<td>8458</td>
</tr>
<tr>
<td>3</td>
<td>Bond</td>
<td>18103</td>
</tr>
<tr>
<td>4</td>
<td>Boone</td>
<td>35351</td>
</tr>
<tr>
<td>5</td>
<td>Brown</td>
<td>6566</td>
</tr>
<tr>
<td>6</td>
<td>Bureau</td>
<td>36036</td>
</tr>
<tr>
<td>7</td>
<td>Calhoun</td>
<td>5167</td>
</tr>
<tr>
<td>8</td>
<td>Carroll</td>
<td>15928</td>
</tr>
<tr>
<td>9</td>
<td>Cass</td>
<td>13727</td>
</tr>
<tr>
<td>10</td>
<td>Champagn</td>
<td>190260</td>
</tr>
<tr>
<td>11</td>
<td>Christian</td>
<td>34543</td>
</tr>
</tbody>
</table>

Figure 12. Screenshot of “County.xls” – Input File

4.3.6 Constraint.xls (optional)

This file includes the budget constraint for each district in each fiscal year. This file is only used when the user chooses to perform the prioritization.
<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
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<td>2010</td>
<td>2010</td>
<td>2011</td>
<td>2012</td>
<td>2013</td>
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<td>30408</td>
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</tr>
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Figure 13. Screenshot of “Constraint.xls” – Input File
CHAPTER 5 SUMMARY AND FUTURE WORK

This project developed an advanced pavement program planning software based on multi-year cost-effectiveness analysis. Existing pavement management programs are reviewed and effective (yet simple) mathematical models are developed to support pavement program planning. Spreadsheet software has been developed to serve as a decision-making support tool that facilitates the planning process. The product of this project will help IDOT staff make better decisions on the cost-effectiveness of MR&R activities.

The software can be upgraded in a few ways, such as:

- Also use IRI and rutting as effectiveness measurements if such information and prediction models are available.
- Only consider the actually repaired part of section in the calculation. This requires such information is provided in the database.
- Consider user costs such as work zone costs and crash costs. This also requires more information in the database.
- Add MCE prioritization option.
- Change "prioritizing for each year separately" and "for all years together" to a general option. So these two approaches can also be selected for ranking and MCE methods.
- Automatically generate alternative projects by changing the project years if such changes are allowed.
- Use backlog requirements as additional constraints in the optimization process.
REFERENCES


APPENDIX A: LAGRANGIAN RELAXATION METHOD FOR PAVEMENT PROJECT PRIORITIZATION

The model of the original prioritization problem can be written as:

Maximize \( z = \sum_{i \in S, j \in Y} \sum_{k \in A_j} e_{ijk} x_{ijk} \)

\( \sum_{j \in Y} \sum_{k \in A_j} x_{ijk} = 1, \quad \forall i \in S \)

\( \sum_{i \in S} \sum_{k \in A_j} c_{ijk} x_{ijk} \leq b_j, \quad \forall j \in Y \)

\( x_{ijk} \in \{0, 1\}, \quad \forall i \in S, j \in Y, k \in A_j, \)

where \( e_{ijk} \) and \( c_{ijk} \) are respectively the effectiveness criterion and the cost of alternative \( k \) in year \( j \) for section \( i \); \( x_{ijk} = 1 \) if alternative \( k \) in year \( j \) for section \( i \) is recommended, 0 otherwise; \( b_j \) is the budget in year \( j \); \( S \) is the set of sections; \( Y \) is the set of years; and \( A_j \) is the set of alternatives in year \( j \) for section \( i \). Do-nothing is considered as a project with zero cost and zero effectiveness.

The relaxed problem is as the follows:

Maximize \( z = \sum_{i \in S, j \in Y} \sum_{k \in A_j} e_{ijk} x_{ijk} + \sum_{j \in Y} \sum_{i \in S} \sum_{k \in A_j} \mu_j \left( b_j - \sum_{i \in S} \sum_{k \in A_j} c_{ijk} x_{ijk} \right) \)

\( = \sum_{j \in Y} b_j + \sum_{i \in S} \sum_{j \in Y} \sum_{k \in A_j} (e_{ijk} - \mu_j c_{ijk}) x_{ijk} \)

\( \sum_{j \in Y} \sum_{k \in A_j} x_{ijk} = 1, \quad \forall i \in S \)

\( x_{ijk} \in \{0, 1\}, \quad \forall i \in S, j \in Y, k \in A_j. \)

where \( \mu_j \) is Lagrangian multiplier and is calculated by the program. So \( x_{ijk} \) is a candidate only if \( e_{ijk} - \mu_j c_{ijk} > 0 \) (i.e., its E/C ratio is larger than \( \mu_j \)). If there are multiple candidates, the one with the largest \( e_{ijk} - \mu_j c_{ijk} \) will be selected.