JOINT TRANSPORTATION RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION
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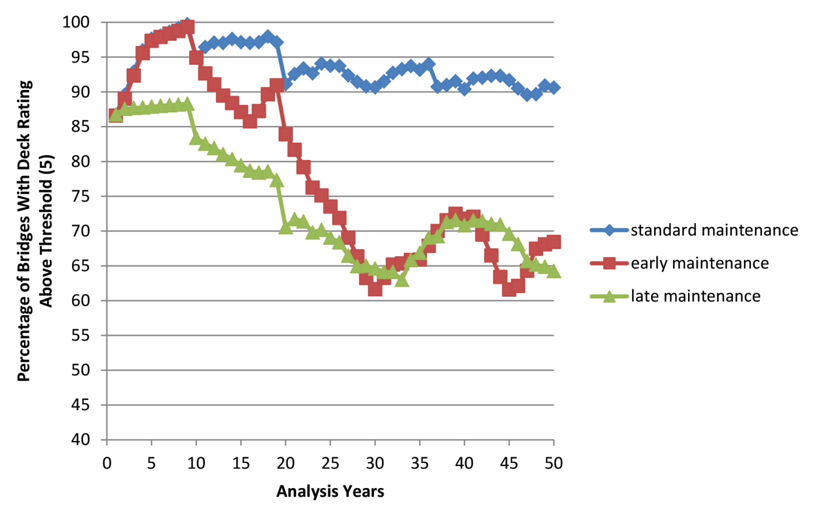
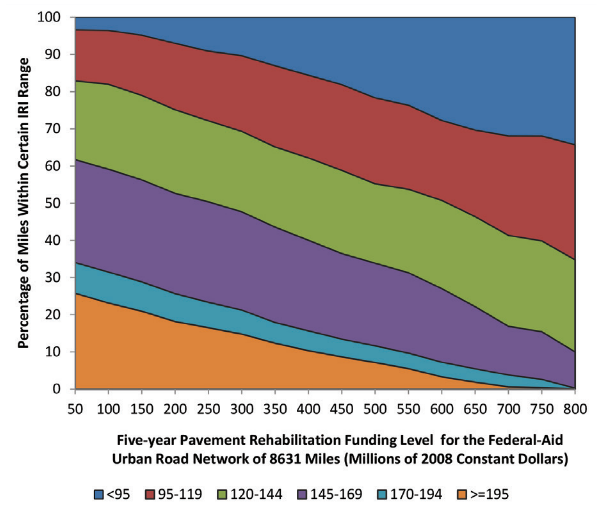
Employing Asset Management to Control Costs and Sustain Highway Levels of Service: Volumes I and II





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JOINT TRANSPORTATION RESEARCH PROGRAM

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16. Abstract

This project investigated the impact of varying two elements of pavement, bridge, and mobility asset management on the long term network-level performance of those assets. The first element was the condition at which restorative treatments are triggered. The second element was the budget available to implement these treatments.

For each of the pavement, bridge and mobility assets, three different management strategies in the form of treatment trigger values were investigated: a standard treatment trigger strategy, an early treatment trigger strategy, and a late treatment trigger strategy. For the pavement and bridge assets, the standard treatment trigger strategy simulates INDOT's current treatment trigger policy. The early treatment trigger strategy simulates performing treatment at a better condition level than the standard treatment trigger strategy, while the late treatment trigger strategy simulates deferring treatment to a worse condition level than the standard treatment trigger strategy.

For bridge assets, each treatment trigger strategy had six different treatments that can be applied to different bridge components. It was discovered that the standard (current) treatment trigger strategy outperforms other strategies.

For pavement assets, the treatment trigger strategies pertained to pavement rehabilitation treatments. It was found that the long-term pavement roughness condition at the network-level is highly influenced by the policy being used to trigger pavement rehabilitation. The higher the trigger standard, the higher the percentage of miles in good condition and the lower the percentage of miles in poor condition.

For mobility management, the treatment trigger strategies pertained to lane additions. It was discovered that neither restricting nor expanding the lane addition project candidate list (corresponding to the late and early treatment trigger strategies, respectively) provides more cost efficiency in the long-term for reducing the percent of road miles or VMT experiencing peak hour congestion.

The report consists of two volumes; the first volume reports the analysis results for the bridge asset class and the second volume reports the analysis results for the pavement and mobility asset classes.

17. Key Words bridge management, pavement management, mobility management, network-level asset condition, treatment trigger	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

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EXECUTIVE SUMMARY

EMPLOYING ASSET MANAGEMENT TO CONTROL COSTS AND SUSTAIN HIGHWAY LEVELS OF SERVICE

Introduction

This project investigated the impact of varying two elements of pavement, bridge, and mobility asset management on the long-term network-level performance of those assets. The first element was the condition at which restorative treatments are triggered. The second element was the budget available to implement these treatments. The feasibility of examining the network-level performance impact of changing safety enhancement treatments' trigger values was limited, and therefore the project did not investigate those impacts.

For each of the pavement, bridge, and mobility assets, three different management strategies in the form of treatment trigger values were investigated: a standard treatment trigger strategy, an early treatment trigger strategy, and a late treatment trigger strategy. For pavement and bridge assets, the standard treatment trigger strategy simulates INDOT's current treatment trigger policy. The early treatment trigger strategy simulates performing treatment at a better condition level than the standard treatment trigger strategy, while the late treatment trigger strategy simulates deferring treatment to a worse condition level than the standard treatment trigger strategy.

For bridge assets, each treatment trigger strategy had six different treatments that can be applied to different bridge components.

For pavement assets, the treatment trigger strategies pertained to pavement rehabilitation treatments. For mobility assets, the treatment trigger strategies pertained to lane additions.

Findings

For bridge management, it was discovered that the standard treatment trigger strategy outperforms the other two strategies. Also, as the budget increases, the standard treatment trigger strategy shows more improvement in its performance. This means that as the budget increases, the standard treatment trigger strategy becomes a better and better option.

For pavement management, the pavement rehabilitation treatment triggers were tested for the State Urban road network, State Rural Arterials and the Federal-Aid Urban road network used to trigger pavement rehabilitation. The following analysis results are contained in Chapter 3.

- The roughness condition of all three pavement road networks is highly influenced by the policy being used to trigger pavement rehabilitation. The higher the trigger standard, the higher the percentage of miles in good condition, and the lower the percentage of miles in poor condition.
- For the State Urban road network, as the funding level increases, the standard being applied to trigger pavement rehabilitation remains a significant factor in increasing the percent of road miles with smooth pavement but progressively becomes a less relevant factor in decreasing the percent of road miles with rough pavement.
- For State-Owned Rural Arterials and Federal-Aid Urban road networks, it was found that for any given funding level, switching from the late treatment trigger strategy to the standard treatment trigger strategy (labeled as Low and Medium Deficiency Standards, respectively, in Volume II of the report) results in a greater magnitude decrease in the percent of roads miles with rough pavement than switching from the standard treatment trigger strategy to the early treatment trigger strategy (labeled as Medium and High Deficiency Standards, respectively, in Volume II of the report).
- At all funding levels for State-Owned Rural Arterials and Federal-Aid Urban road networks, switching from the standard treatment trigger strategy to the early treatment trigger strategy has an effect of greater magnitude in increasing the percent of smooth pavement miles than switching from the late treatment trigger strategy to the standard treatment trigger strategy.

For mobility management, the lane addition treatment triggers were tested for the State Urban and Federal-Aid Urban road networks.

- For the State Urban road network, the standard treatment trigger strategy has more cost-efficient performance than the late treatment trigger strategy at all funding levels in reducing the percent of road miles or VMT traveling on roads with peak hour congestion. Although the early treatment trigger strategy shows more cost-efficient performance than the late treatment trigger strategy at all funding amounts, the early treatment trigger strategy does not seem to be more cost-efficient than the standard treatment trigger strategy at the highest funding levels.
- For the Federal-Aid Urban road network, the effect of the treatment trigger strategy on the network-level mobility condition is more obscure. The standard treatment trigger strategy demonstrates more cost-efficient performance than the late treatment trigger strategy in reducing the percent of VMT traveling on roads with peak hour congestion only at the highest funding levels. Similarly, the early treatment trigger strategy demonstrates nearly the same cost efficiency as the standard treatment trigger strategy in reducing the percent of VMT traveling on roads with peak hour congestion at the highest funding levels.

For safety management, HPMS 2009 data provides two roadway geometry adequacy measures, the horizontal and vertical alignment adequacy measures. These measures were examined to determine if they can be used to construct budget-constrained performance curves that can enhance decision-making in implementing safety restorative projects. However, most urban road sections have no reported alignment adequacy information. Additionally, there is no available information on intersection safety adequacy. Furthermore, the process by which HERS-ST software estimates the influence of alignment correction (safety restorative action) on network-level roadway safety is flawed; the overall crash rate as well as fatality and severe injury rates are calculated for each functional class based purely upon the alignment adequacy measures and roadway geometry, without calibration to the currently observed metrics. It was therefore determined that development of budget-constrained system performance curves for safety management is currently infeasible, but could become feasible if the results of recent JTRP research efforts (SPR-3315 and SPR-3640) are utilized and extended in the future.

Implementation

This research shows that the bridge management strategies used at INDOT are working well. The suggestions below are described in more detail in the report in Volume I, Chapter 5.

1. Continue with current bridge management strategies.
2. Check the bridge management strategies with more treatments, using dTIMS if possible. Test combinations of bridge management strategies. This research tested one constant strategy for the entire 50 year analysis period. Testing variable strategies is recommended.
3. Increase the amount of the bridge management budget to get improved performance, if at all possible.

For the pavement asset class:

1. Use the results shown in Volume II, Chapter 3 (specifically sections 3.3.4, 3.4.4, and 3.5.4) as guidance for decision makers to currently justify retaining or modifying the pavement rehabilitation treatment trigger policy for any anticipated consistent annual budget over a multi-year period.
2. Periodically (every 8–10 years or so) conduct analysis to find the impact of modifying project-level treatment triggers and varying budget availability on the long-term network-level performance of the pavement asset classes. This strategic analysis will enable INDOT to do its best in providing good levels of service on the physical transportation infrastructure while responding to anticipated changes in the consistent annual budget level over a multi-year period.

For the mobility asset class, the analysis of the peak hour congestion condition at the network-level has shown that the lane addition treatment is effective to deploy on the most highly congested roads, typically Interstates and Expressways.

Therefore, INDOT should explore other congestion mitigation strategies to strategically ensure mobility on roads in the future.

This would necessitate the following list of actions:

1. Quantify, with different short-term and long-term mobility measures, the increase in capacity and the user benefits realized by implementing various congestion mitigation treatments (both those that modify or don't modify physical capacity).
2. Quantify the mobility condition "deterioration" that takes place annually or over a period of time for roads of different functional classes and characteristics.
3. Define condition-based policies for triggering congestion mitigation strategies, including for travel demand management strategies such as congestion pricing.

Taking the above actions will enable the analysis conducted in this study to be possible to execute on congestion mitigation treatments other than lane addition.

For the safety asset class:

1. Use the safety screening tool created for Indiana through SPR-3315 to identify high crash locations and screen the safety performance by geographical scope, roadway element, crash type criteria, and roadway feature. The backbone data contained in the tool consists of Indiana road links, intersections, ramps, bridges, and geometric inventory information.
2. Link this tool with a safety asset management software module for the purpose of evaluating network-level safety performance of the highway system in response to funding countermeasures designed to address safety issues.
3. Use the tool in conjunction with the findings of the SPR-3640 research study that is developing a geometry sufficiency index to evaluate the geometric adequacy of road cross-sections based on documented safety and speed effects. This index is being developed to evaluate current deficiencies throughout the network and to aid in prioritizing safety improvement projects.

VOLUME I

EMPLOYING ASSET MANAGEMENT TO CONTROL COSTS AND SUSTAIN HIGHWAY LEVELS OF SERVICE: BRIDGE MAINTENANCE STRATEGIES

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF TERMINOLOGY

Adequate Condition: A bridge component condition rating that is 5 or greater.

Bridge Management Strategy: A method of allocating funding to bridge maintenance and replacement projects. Examples include the standard maintenance strategy, early maintenance strategy.

Early Maintenance Strategy: A bridge management strategy that allows for higher trigger values than the standard maintenance strategy; maintenance and replacement treatments will be performed earlier in the life cycle of the bridge.

Inadequate Condition: A bridge component condition rating that is 3 or lower.

Late Maintenance Strategy: A bridge management strategy that allows for lower trigger values than the standard maintenance strategy for selected maintenance and replacement treatments. With this strategy, maintenance and replacement treatments will be performed later in the life cycle of the bridge.

Maintenance Treatment: A bridge treatment that improves only one component condition rating (either deck condition rating, substructure condition rating, or superstructure condition rating.) Each maintenance treatment has an upper and lower bound for which it can be performed. These upper and lower bounds are referred to as "trigger values."

Performance Jump: An increase in a component condition rating that occurs when a maintenance or replacement treatment is performed on a bridge.

Replacement Treatment: A bridge treatment that improves all three component condition ratings.

Standard Maintenance Strategy: A bridge management strategy that simulates the trigger values currently used by INDOT at which selected maintenance and replacement treatments can be performed.

Threshold Value: A component condition rating used to compare different bridge management strategies.

Trigger Value: An NBI component condition rating at which a maintenance treatment can be performed.

1. INTRODUCTION

1.1 Components of a Bridge Management System

This project explores the relationships between three important parts of bridge management systems: bridge maintenance budgets, bridge component condition ratings, and trigger values. Bridge maintenance budgets provide funds that are used by an agency to maintain the condition of the bridge inventory. A bridge component condition rating is an integer value from 0 to 9 that indicates the amount of deterioration that part of the bridge has experienced (Federal Highway Administration, 2012). A trigger value indicates the condition rating at which to perform maintenance activities on a bridge. When the trigger value is reached, this indicates that the maintenance activity should be performed before the condition rating decreases further. Figure 1.1 shows how the three parts of the bridge management system interact with each other.

For bridges, this project will use the National Bridge Inventory (NBI) condition ratings to measure the asset condition. The NBI condition ratings are a measure of the performance of the bridge. These ratings are done for different components of the bridge, and are called component ratings. The components that are rated are the bridge deck, the superstructure, and the substructure. These ratings are an integer value between 0 and 9. A bridge with a rating of 0 is considered to be a failed bridge, which is out of service or unable to be repaired. A bridge with a rating of 9 is considered to be in excellent condition. If any one of the component condition ratings is 0, 1, 2, 3, or 4, then the bridge is considered to be structurally deficient (Federal Highway Administration, 2012).

The Indiana Bridge Management System (IBMS) was developed by Purdue University. IBMS combines budget information, asset condition information, project information, and life cycle cost analysis. From this information, the system recommends a program of bridge projects (Sinha, et al., 2009). Because the IBMS code is no longer available in a form suitable for research purposes, this project developed a simplified version of IBMS, which is called the Bridge Management Research Software (BMRS). BMRS produces results that can be used to explore the relationships shown in Figure 1.1. BMRS takes budget information and maintenance project information, and uses that information to evaluate specified trigger values for specific maintenance activities.

This report will continue to refer to several different terms that are important for understanding the relationships between different parts of bridge management systems. To help avoid confusion, the “List of Terminology” section at the beginning of this report includes a glossary of some of the important terminology used in this report.

1.2 Data Elements

One of the most important elements in the bridge management system is the budget information. In a given year, there will be more possible projects than the budget can fund. This means that the system must be able to select certain projects from all the possible projects. With a limited budget, making the best use of that budget can help to keep statewide assets in the best possible condition.

As the level of investment changes, it is expected that the overall condition of bridges in Indiana will change. This change in overall statewide bridge condition is measured by finding the percentage of bridges that are above a certain user-specified NBI condition value. It is expected that, as the level of investment increases, the overall asset condition will improve. Similarly, it is expected that, as the level of investment decreases, the overall statewide asset condition will worsen.

1.3 Research Process and Expected Results

Figures 1.2 and 1.3 show the process for assessing the system impact of changing budget levels and trigger values. Because there are many different ways to perform bridge maintenance, each different method is

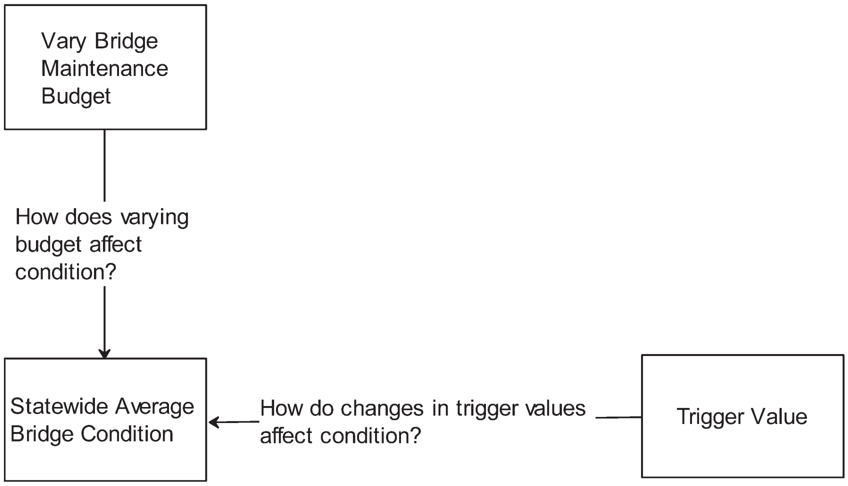


Figure 1.1 Relationships between bridge maintenance budget, trigger values, and statewide average bridge condition.

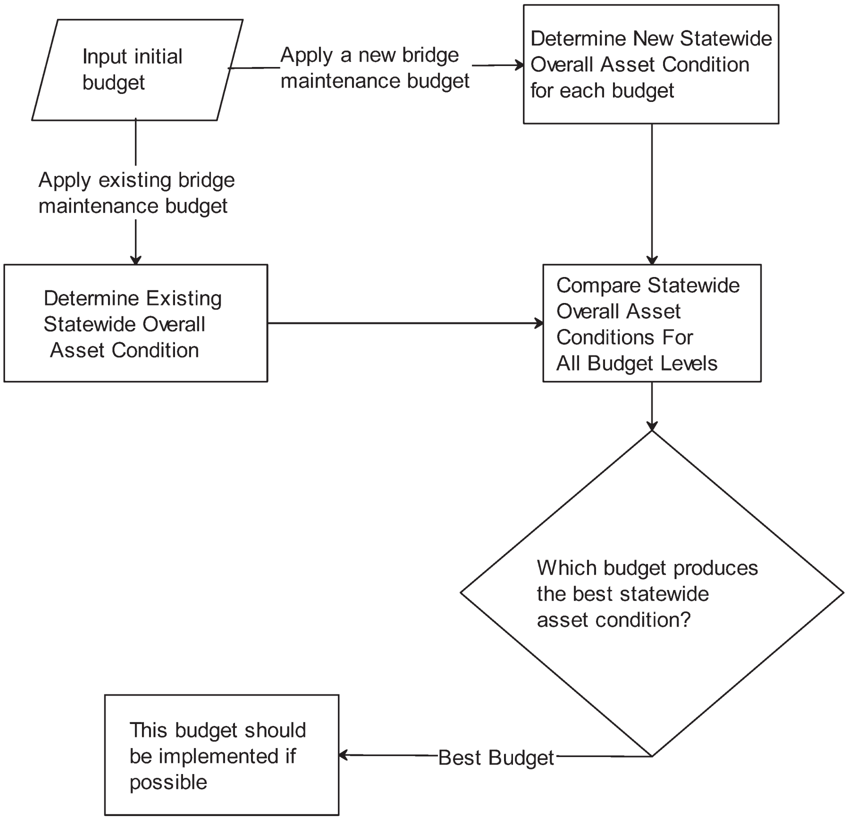


Figure 1.2 Process of evaluating different budget levels.

defined as a different bridge management strategy. This project evaluates three different bridge management strategies: standard maintenance, early maintenance, and late maintenance. The details of these bridge management strategies are available in Section 3 of Chapter 3. Because the trigger values may be different for different treatment types, the processes shown in Figures 1.2 and 1.3 are repeated for each run. The process in Figure 1.2 evaluates the effectiveness of different budget levels. After the budget levels and trigger values have been defined for each bridge management strategy, the process in Figure 1.3 is used to compare each bridge management strategy.

The process shown in Figure 1.3 represents the research process in this project. More details on specific parts of this process are discussed in later sections of this report. Condition rating distribution analysis is explained in Section 1 of Chapter 4. Threshold analysis is explained in Section 2 of Chapter 4. The index function used in this project is explained in Section 3 of Chapter 5.

Each component condition rating is a discrete value, so the trigger values will be discrete variables. Each trigger value has an upper and a lower bound. During the BMRS modeling process, component condition ratings can become non-integer values because of the deterioration modeling BMRS uses, which is discussed in more detail in Section 3 of Chapter 3. However, the upper and lower bounds for a trigger value will always remain discrete variables, and a bridge with a component that has a condition rating that lies between the upper and lower bound of a trigger value can still have that treatment applied, even if the component condition rating is a non-integer value.

There are some component condition ratings that do not make sense to consider as potential trigger value upper or lower bounds for this project. The trigger value cannot be 9, because that is the highest rating a bridge can achieve, and bridges in the best possible condition do not need to be treated. The trigger value cannot be 0, because at that point the bridge has failed, and must be reconstructed, instead of having a maintenance activity performed.

Because the model developed in this project will be using data from bridge maintenance and replacement projects, this information must be accurately represented in the model. This information will be different for different maintenance activities. Each maintenance activity will change at least one of the component condition ratings. Depending on the maintenance activity that is performed, different component condition ratings will improve. Even if one component condition rating is improved by a treatment; other component condition ratings may not be affected. For example, replacing the deck of a bridge will only improve the deck condition rating. This change in condition rating that a component experiences will be included in the BMRS analysis. If, for example, a maintenance treatment incurs an improvement

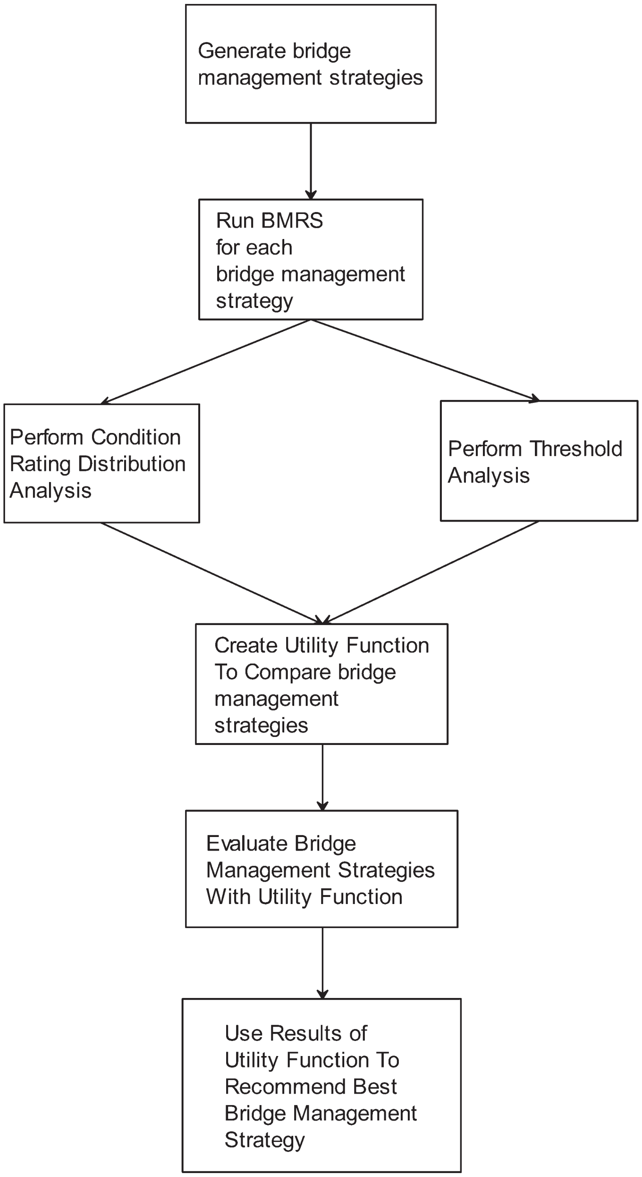


Figure 1.3 Process of evaluating different bridge management strategies.

in the condition rating from 3 to 7, that component experiences a “performance jump” of 4 units. By performing a treatment such as replacing the bridge deck, BMRS applies the new condition rating from the performance jump to the bridge deck after the bridge deck is replaced.

1.4. Report Structure

This report is organized as follows. Previous research on bridge management systems, condition modeling, and life cycle cost analysis is contained in Chapter 2. The data used will also be discussed in Chapter 2. The mechanics and development of BMRS will be detailed in Chapter 3. The results of the BMRS model will be in Chapter 4. Recommendations will be in Chapter 5. A discussion of the attempted troubleshooting of IBMS is in Appendix A. A BMRS user’s manual is in Appendix B.

2. LITERATURE REVIEW AND DATA SYSTEMS

2.1. Bridge Management Systems

The FHWA defines a bridge management system as follows: “A systematic process that provides, analyzes, and summarizes bridge information for use in selecting and implementing cost-effective bridge construction, rehabilitation, and maintenance programs” (FHWA, 2012). A bridge management system often includes software, but is not limited to only software. The State of Indiana used to use a bridge management software package called the Indiana Bridge Management System (IBMS). That bridge management software package has since been replaced by a software package called dTIMS.

With limited funding, decisions must be made to best use available funds on maintaining Indiana’s bridge network. Because dTIMS was unavailable for use on this project, IBMS was considered for use on this project, and BMRS results were chosen to be used in place of IBMS results, it is important to understand how both IBMS and BMRS works. The details of how BMRS works are discussed in Chapter 3. IBMS uses a system of modules to make investment decisions that allocate funds to different bridge maintenance projects. There are four different modules in IBMS: the Decision Tree Module (DTREE), the Life-cycle Economic Analysis Module (LCCOST), the Project Ranking Module (RANK), and the Optimization Module (OPT). Figure 2.1 explains how the different modules interact. In order for each module to work, the previous module must be completed first. If there is an error in one module, IBMS cannot move to the next module (Sinha, et al., 2009).

AASHTOW are Bridge Management software is another example of a bridge management system. This software was formerly known as PONTIS. This software allows users to keep a record of bridge maintenance and replacement treatments. This software allows users to work with element level inspection data. Element level inspection data is much more detailed than traditional NBI data. Instead of only using condition ratings for the deck, superstructure, and substructure, element level inspection data gives much more specific information on the condition of different parts of a bridge. This gives users much more detailed information to make maintenance decisions (American Association of State Highway and Transportation Officials, 2013).

Orcesi and Frangopol (2010) proposed a probabilistic approach to determining optimal maintenance strategies for bridges. This approach relies on measuring the strain on the girders of a bridge with sensors, and then performing a statistical analysis on the data collected. The statistical analysis determines the probability of a girder failing, which means that it goes below a predefined failure threshold. This probability is put into a formula to calculate an expected failure cost

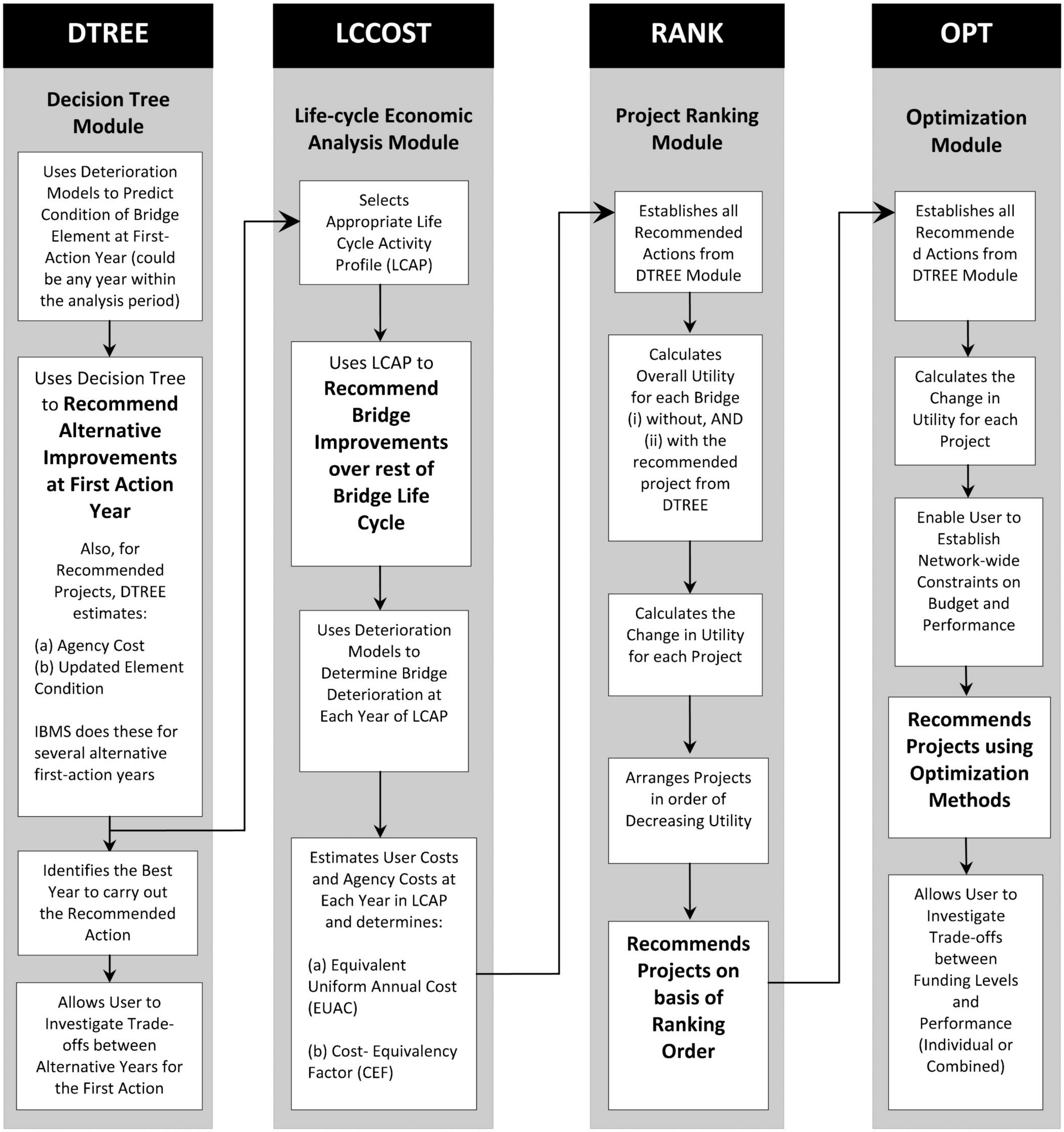


Figure 2.1 IBMS modules and their primary functions (Sinha et al., 2009).

for each component, which is then used to calculate a system failure cost. The system failure cost is used to determine the best time to perform a maintenance action. It is also assumed that because statistical analysis is used to help determine the best time to perform a maintenance action, that there will be some error in the decision of the best time to perform a maintenance action. The system management costs and the available budget are also needed for this approach. An optimization is performed to minimize the failure cost, error in decision making, and system management costs. Given the available funds, this optimization creates a maintenance strategy that meets the predefined performance thresholds.

2.2. Condition Modeling

Because bridges are important parts of a transportation network, it is important to know when maintenance should be performed on a bridge. However, bridge condition ratings reflect only the current state of the bridge; they do not give any information on what the bridge will be like in the future. Bridge condition modeling allows for prediction of the condition of the bridge in future years. Bridge condition modeling takes current condition information and data about bridge characteristics, and predicts how the bridge condition rating will change in future years if no maintenance is performed.

Markov chains are one method for modeling how a bridge deck will deteriorate from one condition state to another. Cesare, Santamarina, Turkstra, and Vanmarcke (1992) proposed such a model, based on data from New York bridges. The model is a probabilistic model, based on what condition state the bridge is currently in. These probabilities were determined for both steel bridges and concrete bridges. For each condition state, the model assumes an initial statistical distribution. Based on this assumed distribution, the model performs statistical analysis that results in a matrix of probabilities that a bridge will deteriorate from one condition state to the next. To use the model, bridge condition data for a given year are used. For each bridge in a certain condtion state, that bridge will either stay in the same condition state in the next year, or it will deteriorate to the next state. After it is determined which bridges will deteriorate to the next condition state and which will stay at the same condition state, the resulting condtion states become the condition states for the next year. This is repeated year after year, until a bridge deteriorates to the lowest possible condition state. This model does not take maintenance into account. The model says that bridges will only deteriorate; if maintenance is performed, that change in condition state must be input by a user.

A genetic algorithm is also a possible method to model the deterioration of a bridge deck. Liu, Hammad, and Itoh (1997) proposed one such algorithm. A genetic algorithm is able to process a large number of possible solutions, and can easily have multiple decision variables. This algorithm generates possible solutions and then picks one based on pre-defined selection criteria.The solutions are for the entire network of bridges. The solution is Pareto optimal, and illustrates the tradeoff between rehabilitation cost and the amount of deterioration. This allows the user of the algorithm to see how much deterioration can be expected at a given budget level.

Another way to model the deterioration of bridge decks is an artificial neural network model. Huang (2010) developed this type of model. This model was developed using data from bridges in Wisconsin. To find the statistically significant inputs for the artificial neural network model, the data used were condition ratings from bridge inspectors, records of maintenance work performed on the bridges, and inventory data from the bridge management software program PONTIS. For all inputs, statistical testing was performed to find the p-values of possible inputs at a 95% confidence level. For bridges that had deck maintenance performed on them, the data were analyzed to find the how the maintenance history affected the deterioration of the deck. For bridges with no maintenance performed on them, the distribution of deck condition ratings was determined. Inventory data for bridge decks were studied, which found eleven parameters that influence deck deterioration. The inputs that were found to be significant were maintenance history, age of the bridge, previous condition, the district the bridge was located in, the design load, length of the bridge, bridge deck area, ADT, the environmental condition the bridge was exposed to, the number of spans, and the degree of skew. Once the significant input parameters are found, the artificial neural network model is created and can be used to find bridge deck deterioration.

Lee et al. (2012) proposed an artificial intelligence model for bridge deterioration. This model first uses a backwards prediction model to fill in gaps in historical data. If condition ratings are unavailable, the backwards prediction model will produce an estimated rating for the unavailable components or years of data. The model then uses time delay neural network modeling to predict future component condition ratings. The time delay neural network modeling is similar to the artificial neural network model proposed by Huang in 2010.

Although there are many different types of deterioration modeling that have been developed, this project uses deterioration equations taken from IBMS. These equations are included in the report for SPR-3013: *Updating and Enhancing the Indiana Bridge Management System* (Sinha et al., 2009). More details about how these deterioration equations are used in BMRS are in Section 3 of Chapter 3.

2.3. Life Cycle Cost Analysis

When comparing maintenance alternatives, cost is often one of the most important factors in selecting an alternative. Some alternatives may cost less initially, but may also have to be performed more frequently to maintain the condition of the bridge. This makes it important to compare costs for maintenance alternatives over the whole life of the bridge, in order to find alternatives that will cost the least over the life of the bridge.

Yang and Hsu (2010) developed a framework to analyze the life cycle costs of a bridge. The life cycle cost incorporates the time value of money to compare different maintenance operation alternatives. Due to inflation, all the costs of maintenance alternatives must be converted to a net present value so that they can be compared. There is uncertainty in statistical modeling, so to deal with the uncertainty in the modeling of life cycle costs, a Monte Carlo simulation was used to model the life cycle cost from bridge construction to the first maintenance operation. The Monte Carlo simulation also models the time interval to subsequent maintenance operations. From this information, Yang and Hsu developed a ε-constrained particle swarm optimization algorithm. This algorithm models a trade-off between life-cycle costs and performance indicators, such as condition ratings.

It is possible that, instead of performing periodic maintenance on a bridge, the bridge can simply be replaced with a new bridge at any point in the life of the bridge. It is also useful to compare the cost of maintenance activities to the cost of bridge replacement in order to find the cost if maintenance is not performed before the bridge fails. Rodriguez, Labi, and Li (2006) developed a set of models for these bridge replacement costs. There are different models for steel bridges, concrete slab bridges, concrete box beam bridges, concrete I-beam bridges, and concrete T-beam bridges. For each of these categories, models were divided into the following types of bridge replacement costs: superstructure replacement, substructure replacement, approach cost, and other costs. Superstructure costs include items such as concrete material costs, steel material costs, and costs of other items needed to construct the bridge deck. Substructure costs are items such as construction of piles and construction of footings. Approach costs include guardrails, fences, pavements, and site preparation. Other costs include clearing right-of-way, excavation, traffic control during construction, and the cost to remove the existing structure. The model types used were linear, Cobb-Douglas production function, transformed Cobb-Douglas, or constrained Cobb-Douglas. The Cobb-Douglas function is a homogenous input-output function. The inputs used are different physical characteristics of the bridge, and the output is the replacement cost. The replacement cost can then be compared to the cost of other maintenance strategies on a bridge to determine the point in the life of the bridge when replacement is financially beneficial.

Hawk (2003) proposed a stochastic approach to life cycle cost analysis. This approach helps to determine the service life. This approach requires data on maintenance costs, current bridge condition, the time value of deferring maintenance, and several other data items. The time value of deferring maintenance is a way of measuring the costs of waiting to perform maintenance on a bridge. If a treatment is not performed at a certain point in the life cycle of a bridge, there may be additional costs to perform that same treatment at a later point the life cycle of the bridge. This approach allows for several different models to be used. Once a model is picked by a user, the reliability of the results of that model must be analyzed. Because of uncertainty in some of the parameters used in this stochastic approach to life cycle cost analysis, uncertainty modeling must be used. Uncertainty modeling helps users of this approach to know how reliable the results produced by their model are.

2.4. Project Data

To investigate the relationships between trigger values, budget, and performance measures, raw data must be processed in some way. This project uses raw data as input for BMRS and as performance measures. The raw data used as input are put into BMRS so that BMRS can select bridge maintenance and replacement projects to perform in a given year. The raw data used as performance measures explain how efficiently bridges are performing.

The original intention of this project was to use IBMS for modeling, however some complications arose. (See Appendix A.) BMRS was created as a simplified substitute for IBMS to allow the researchers to simulate IBMS results. Because IBMS is the basis for BMRS, Section 5 will show the required data items for IBMS. Details on how BMRS works are covered in Chapter 3.

2.5. IBMS Data Requirements

Before evaluating a bridge management strategy, IBMS needs several data items as input. The input data items that are used by IBMS can be divided into several categories. Table 2.1 shows a list of the input items IBMS uses from each category: inventory data, traffic data, bridge physical data, bridge condition data, and maintenance data. Inventory data items are data that indicate the location of a bridge or are administrative data used by INDOT. Traffic data items are data about the traffic that crosses a bridge. Bridge physical data items are data about how a bridge is constructed. Bridge condition data items are the NBI condition ratings for different parts of a bridge. Maintenance data items are data that are related to previous maintenance performed on a bridge and proposed future maintenance for that bridge.

To measure the performance of bridges, the data items used are NBI condition ratings. Table 2.2 shows how each NBI condition rating is related to the physical state of a bridge component.

2.6. BMRS Data Requirements

BMRS requires fewer data items as input. The data items for BMRS are:

(1) Structure Number. This item is used to identify each bridge in the network. It is field 008 in the NBI data dictionary.
(2) Deck condition rating. This item is field 058 in the NBI data dictionary. An explanation of the meaning of each condition rating is given in Table 2.2.
(3) Substructure condition rating. This item is field 060 in the NBI data dictionary. An explanation of the meaning of each condition rating is given in Table 2.2.
(4) Superstructure condition rating. This item is field 059 in the NBI data dictionary. An explanation of the meaning of each condition rating is given in Table 2.2.
(5) Year of last maintenance performed on bridge deck. This item is derived from field 106C in the NBI data

TABLE 2.1
Data items in input data categories (Sinha et al., 2009)

Category	Data items
Inventory data	Highway route number, county code, bridge number, bridge designation (type of bridge), district code, functional class code, highway system of inventory route, parallel structure designation, road reference point, latitude, longitude
Traffic data	Average daily traffic (ADT), number of lanes of traffic, detour length, direction of traffic, functional class code for highway under the bridge
Bridge physical data	Total width of bridge deck, clearance width of bridge deck, bridge length, bridge vertical clearance, superstructure material type, superstructure design type, type of loading, deck geometry code, vertical clearance over bridge roadway, reference feature for vertical clearance under bridge, horizontal clearance under bridge to the right, reference feature for horizontal clearance, substructure height, culvert rise, culvert width, culvert barrel length, total deck patching area, patching area as a percentage of total deck area, joint length, type of joint
Bridge condition data	Deck condition rating, superstructure condition rating, substructure condition rating, wearing surface condition rating, culvert condition rating, joint condition, structural evaluation code
Maintenance data	Proposed work code, year of original construction, date of last inspection, length of bridge improvement (for the approach)

dictionary. NBI data does not differentiate between components when it lists when maintenance was last performed; NBI data only includes the year any maintenance was performed.

(6) Year of last maintenance performed on bridge substructure. This item is derived from field 106C in the NBI data dictionary.

(7) Year of last maintenance performed on bridge superstructure. This item is derived from field 106C in the NBI data dictionary.

These data items are all taken from the NBI data collected by INDOT (Federal Highway Administration, 2012). For this project, these data items are taken from the BridgeInspectTech database maintained by INDOT.

2.7. Selecting Trigger Values

To decide when to perform different treatments on bridges, trigger values need to be selected to determine the ideal time to perform the appropriate maintenance operations. These trigger values may vary by bridge component and treatment type. Because maintenance operations affect only certain areas of the bridge, the trigger value for a treatment will be a condition rating for the component that is treated. With these basic considerations in place, the process of selecting ideal trigger values can begin.

The first step in selecting trigger values is to establish the set of possible trigger values. Only certain values of the NBI component condition ratings can be put into the set of possible trigger values. For each component, the set of possible trigger values that will be used for this project includes 2, 3, 4, 5, 6, and 7. This means that 1, 8, and 9 are the NBI condition ratings that are not included in the set of possible trigger values. A condition rating of 1 indicates that the bridge is about to fail, and it is not in service. Because the bridge is out of service, this will affect the network, and maintenance or replacement will have to be performed on the bridge before it can be put back in service. This will be very expensive, both for the users and for the agency. These costs come from maintenance costs and the costs to users who cannot use the bridge. A condition rating of 8 indicates that the bridge has no problems that are noted. This means that maintenance will not be cost

TABLE 2.2
Description of NBI condition ratings for bridge components (Federal Highway Administration, 2012)

NBI condition rating	FHWA description of condition rating
1 - Imminent failure condition	Major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put it back in light service.
2 - Critical condition	Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
3 - Serious Condition	Loss of section, deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present.
4 - Poor Condition	Advanced section loss, deterioration, spalling or scour.
5 - Fair Condition	All primary structural elements are sound but may have minor section loss, cracking, spalling or scour.
6 - Satisfactory Condition	Structural elements show some minor deterioration.
7 - Good Condition	Some minor problems
8 - Very Good Condition	No problems noted
9 - Excellent Condition	Bridge is in best possible condition

effective, because it cannot improve the bridge condition very much. Similarly, performing maintenance on a bridge with a condition rating of 9 will not improve the condition of the bridge, so it will not be cost effective.

The next step is to establish a performance threshold to measure the effectiveness of different trigger values. The performance threshold is a chosen component condition rating for a bridge component. The performance threshold will be the same for each trigger value, so that they can be compared. The percentage of bridges that are above the threshold will be found for each trigger value. The higher the number of bridges above the threshold, the more effective a trigger value is. For this project, a few different component condition ratings will be chosen as thresholds. The threshold value and the trigger value are not dependent on each other. The threshold value is only used for the purpose of comparing different trigger values. A threshold value may be the same as one of the trigger values in the set of trigger values, but the threshold value does not have to be the same as the selected trigger value. The trigger value can be greater than, less than, or equal to the threshold value.

The results for each trigger value can be compared. At a given budget level, the trigger value with the highest percentage of bridges above the threshold will be considered the best trigger value. Because the trigger values are for individual treatments, different trigger values can be chosen for different treatments to form an overall maintenance strategy that is cost effective.

For example, if a threshold value of 5 is chosen; trigger values of 3, 4, and 5 can be compared. For all of these trigger values, the percentage of bridges above the threshold value of 5 is determined. If it is found that a trigger value of 3 will put 40% of bridges above the threshold rating of 5, a trigger value of 4 will put 45% of bridges above the threshold rating of 5, and a trigger value of 5 will put 40% of bridges above the threshold rating of 5; then a trigger value of 4 would be the most effective for a threshold of 5. This process can be repeated as desired for different combinations of trigger values, budget values, and threshold values.

The process of the analysis for the combinations of trigger values and threshold values needs to be replicable, because this process allows for comparisons of trigger values and threshold values. For example, threshold values of 4 and 6 can be compared. If 4 is used as a threshold value, then the percentage of bridges above the threshold will indicate the number of bridges that are above a condition rating of “poor.” If 6 is used as a threshold, then the percentage of bridges above the threshold will indicate the number of bridges that are above a condition rating of “fair.” These thresholds represent two different standards of acceptable performance.

Once a threshold is chosen, BMRS is used to determine which projects the available budget should be spent on. From this bridge management strategy at each budget level, the change in condition ratings for the bridge network is determined, again using BMRS. The changes in condition ratings come from the maintenance performed on selected bridges and from natural deterioration. After the changes in component condition ratings have been determined for all the bridges in the network, the percentage of bridges above and below the chosen component threshold is found. For each bridge management strategy, the percentage of bridges above the chosen threshold is graphed over the whole analysis period. Figure 2.2 shows an example of the format of one of these graphs.

When using the results produced by BMRS, users can only look at the budget levels that are put into BMRS for this project. Because of this limitation, it is important to develop a method where a user can take a budget or trigger value that is not one of the values used in the analysis and estimate the percentage of bridges

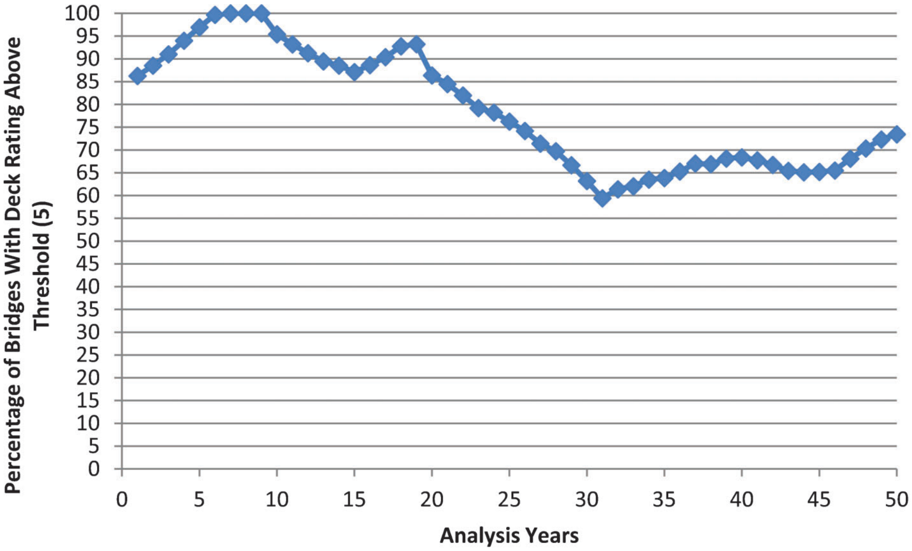


Figure 2.2 Example format of percentage of bridge decks above the threshold over analysis period.

that will lie above the threshold value. Appendix B includes a "user's manual" so that future researchers can use BMRS to explore new budgets and trigger values.

3. RESEARCH PROCESS AND DEVELOPMENT OF BMRS

3.1. Introduction to BMRS

The IBMS software that was developed at Purdue was used for many research projects after it was developed. This software was also used for bridge asset management decisions by the Indiana Department of Transportation. The Indiana Department of Transportation now uses the dTIMS system, which is based on similar modeling concepts. Although this system is available to decision makers at INDOT, it is not available for use by researchers. In projects where bridge management concepts are being researched, IBMS results can be used to approximate dTIMS results (specifically the "dTREE" module of IBMS). However, as experience on this project has shown, a researcher may not be able to get IBMS to run correctly on a computer (see Appendix A). Spending time troubleshooting IBMS proved to be a very inefficient use of research time. In order to avoid further delays with the IBMS software, a new software package, Bridge Management Research Software (BMRS), was developed. BMRS implements the key elements of IBMS logic, but in a simplified way. This chapter documents the use of BMRS, should other researchers choose to use it.

There are a few key differences between BMRS and IBMS that a researcher must keep in mind when using BMRS to approximate IBMS results. IBMS allows for 55 different treatment types to be performed. These treatments all have unique treatment codes. Of these 55 treatment types, 31 affect more than one of the three major bridge components used by BMRS: bridge deck, substructure, and superstructure. IBMS also allows for widening of a bridge or raising/lowering a bridge (Sinha, et al., 2009). By contrast, the only BMRS treatment that affects more than one bridge component is the replacement treatment. BMRS also does not allow for widening of a bridge or raising/lowering a bridge. Because of this, BMRS is not able to produce the same level of detailed results that IBMS does. However, BMRS can still be used to explore how one general strategy compares to another over an analysis period.

For this project, BMRS is not used to develop highly specific maintenance strategies. Instead, BMRS is used to model relationships between strategies. BMRS will explore the differences in the effectiveness of these strategies. Figure 3.1 shows a flowchart of how BMRS works. A similar (and much more complex) diagram for the "dTREE" module of IBMS is available in the addendum to Chapter 3 of SPR-3013: *Updating and Enhancing the Indiana Bridge Management System* (Sinha et al., 2009).

3.2. BMRS Input

BMRS uses a data input file that is constructed by the user. The data input file is in the form of a Microsoft Excel spreadsheet, as shown in Figures 3.2 and 3.3. For BMRS to work properly, the columns must be labeled and formatted as shown in these figures.

The first data item in the input file is the bridge number. This is required so that the user can define the set of bridges that BMRS will perform analysis on. The second data item in the input file is the different component condition ratings. BMRS requires a deck condition rating, superstructure condition rating, and substructure condition rating. These condition ratings represent the condition of the bridge at the start of the analysis period, before BMRS performs the modeling that will update these ratings. The third data input item that is required is the most recent repair year for each component. This item represents the last time that maintenance was performed on each component of the bridge. It is important that the last repair year is component specific. This is especially important in cases where maintenance was performed in different years on different elements of the same bridge. For example, if maintenance on the bridge deck was performed in the year 2000, and maintenance on the superstructure was performed in the year 2005, the last repair year for the bridge deck (column E in Figure 3.3) will be 2000 and the last repair year for the superstructure (column F in Figure 3.3) will be 2005. This input item will be used in the bridge deterioration models that BMRS will apply.

In addition to the data input file, BMRS will also ask the user to input different values using text boxes, drop down lists, and radio buttons. The analysis period, budget scenario, and treatment data are all examples of user input by text boxes, drop down lists, and radio buttons.

During the analysis period, each bridge component will deteriorate, be considered as a candidate for treatment, and then have any selected treatment actions performed. Figure 3.4 shows the analysis period input screen.

The next user input item that is required is a budget. Figure 3.5 shows the budget input screen. In this figure, there are two different budget values that are input. The different budget items are as follows:

(1) Maintenance budget: The first budget item, "enter budget for year x" is the budget that will be used for maintenance treatments.
(2) Replacement budget: The second budget item, "Enter replacement budget for year x" is the budget that will be used for replacement treatments.

These two budget values are separate from each other. The "enter budget for year x" item is only for the maintenance budget, and the "enter replacement budget for year x" is only for the replacement budget. This means that in Figure 3.5, the total budget is

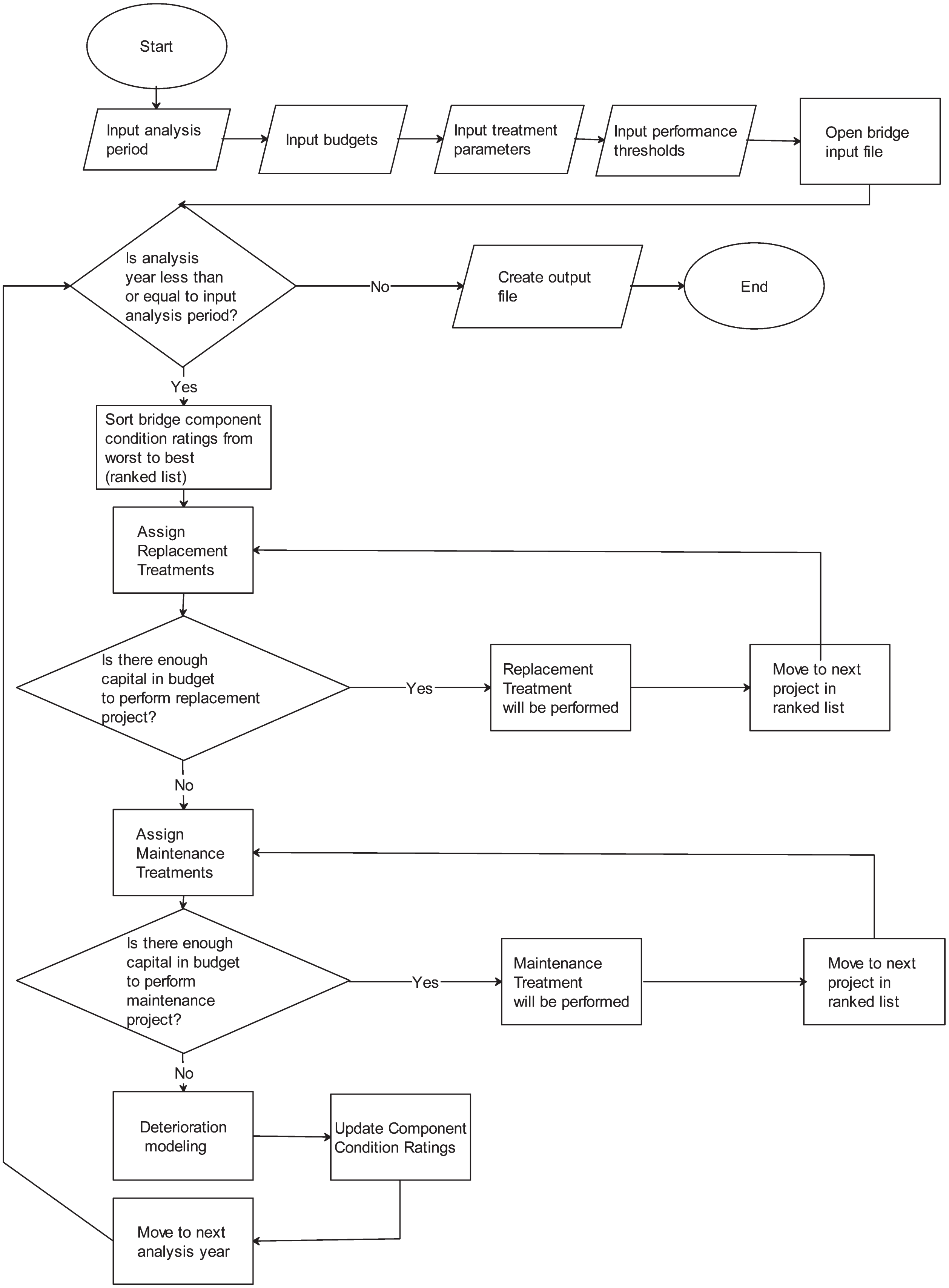
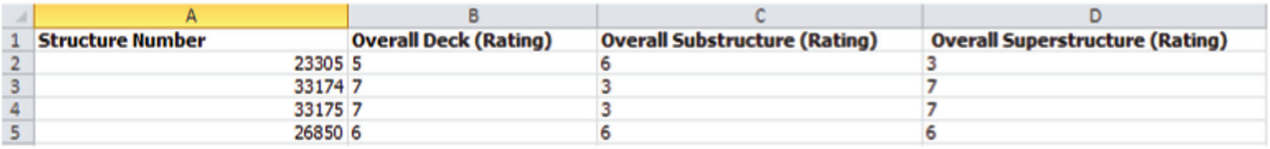


Figure 3.1 BMRS process flowchart.



	A	B	C	D
1	Structure Number	Overall Deck (Rating)	Overall Substructure (Rating)	Overall Superstructure (Rating)
2	23305	5	6	3
3	33174	7	3	7
4	33175	7	3	7
5	26850	6	6	6

Figure 3.2 BMRS input Excel file, columns A through D.

110,374,880 (this is found by adding 100,221,550+ 10,153,330). BMRS is used to replicate IBMS treatment types. The overall budget is split into replacement and maintenance budgets, and each part of the budget is applied to different BMRS treatments. Table 3.1 shows the treatments used and which budget item applies to which treatment.

When a researcher would like to use a constant budget over the full analysis period, once both of the budget values are input for the first year, the "copy values" button at the bottom of the screen will copy the budget from the first year into all other years in the analysis period. BMRS does not account for inflation in the budget or increases in construction costs over time. Future researchers may seek to add such features to BMRS.

The next user input item is the replacement treatment input screen in Figure 3.6. A replacement treatment will give a "performance jump" to the deck, substructure, and superstructure of a bridge, instead of just one of those components. The cost for a replacement treatment is input into the "enter replacement cost" text box. For this project, a replacement cost of $3,517,000 was used. The "enter resultant state for replacement drop down box" represents the condition rating that each bridge component will get to when the replacement treatment is applied.

The final user input item that BMRS requires is treatment data. Figure 3.7 shows the input screen for one bridge treatment type. Treatments are input one at a time. The components of a treatment input are given in the following list:

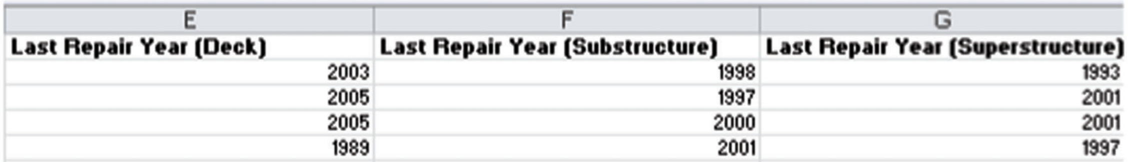
(1) The "treatment name" text box requires a user input of text or symbol characters.
(2) The bridge component that the treatment applies to. There are 3 radio buttons that the user can select from, one for each bridge component in the data input file.
(3) The "Enter treatment cost" text box requires a user input of numerical characters only.
(4) The "Enter Lower Bound," "Enter Upper Bound," and "Enter Resultant State" drop down boxes represent the boundary conditions for the treatment. The lower bound is the minimum condition rating at which that specific treatment is considered feasible. If the bridge component condition is lower than the minimum condition rating, then that treatment will not be used on the bridge. The upper bound is the maximum condition rating at which that treatment will be applied. If the bridge component condition is higher than the maximum condition rating, then that treatment will not be used on the bridge. The resultant state is the condition rating which the bridge component will be in if the treatment is applied to the component. This represents the "performance jump" that the bridge component experiences from the treatment.

After the first treatment is entered, the user may want to put in more treatments for consideration. To add another treatment, the user simply has to use the "Add More" button at the bottom of the screen. Once all the desired treatments have been added, the "Finish" button at the bottom of the screen will move BMRS to the modeling portion of its analysis.

3.3. Modeling

Once the user has finished entering the input items into BMRS, the software begins the process of sorting bridge elements by their initial condition ratings to determine which bridge component should receive treatment first. BMRS sorts each component from minimum (worst) condition rating to maximum (best) condition rating. The bridge components with the worst condition ratings will be treated first.

Table 3.2 gives an example in which BMRS sorts 4 bridges with the bridge deck ratings shown. BMRS will sort these deck ratings as follows: 3, 5, 6, and 7. Therefore, for these 4 bridges; BMRS will sort them in the following order for treatment: 33174, 23305, 26850, and 33175. (This means that BMRS will recommend that deck of bridge 33174 will be treated before any of the other 3 bridges.) If the same bridges mentioned in Table 3.2 have the given substructure condition ratings, BMRS will sort the substructure ratings as follows: 2, 4, 5, and 6. Therefore, for the substructures of these bridges; BMRS will sort them in the following order for treatment: 33175, 23305, 33174, and 26850. Even though bridge 33174 was the first candidate for treatment for the bridge deck, bridge 33175 is the first



E	F	G
Last Repair Year (Deck)	Last Repair Year (Substructure)	Last Repair Year (Superstructure)
2003	1998	1993
2005	1997	2001
2005	2000	2001
1989	2001	1997

Figure 3.3 BMRS input Excel file, columns E through G.

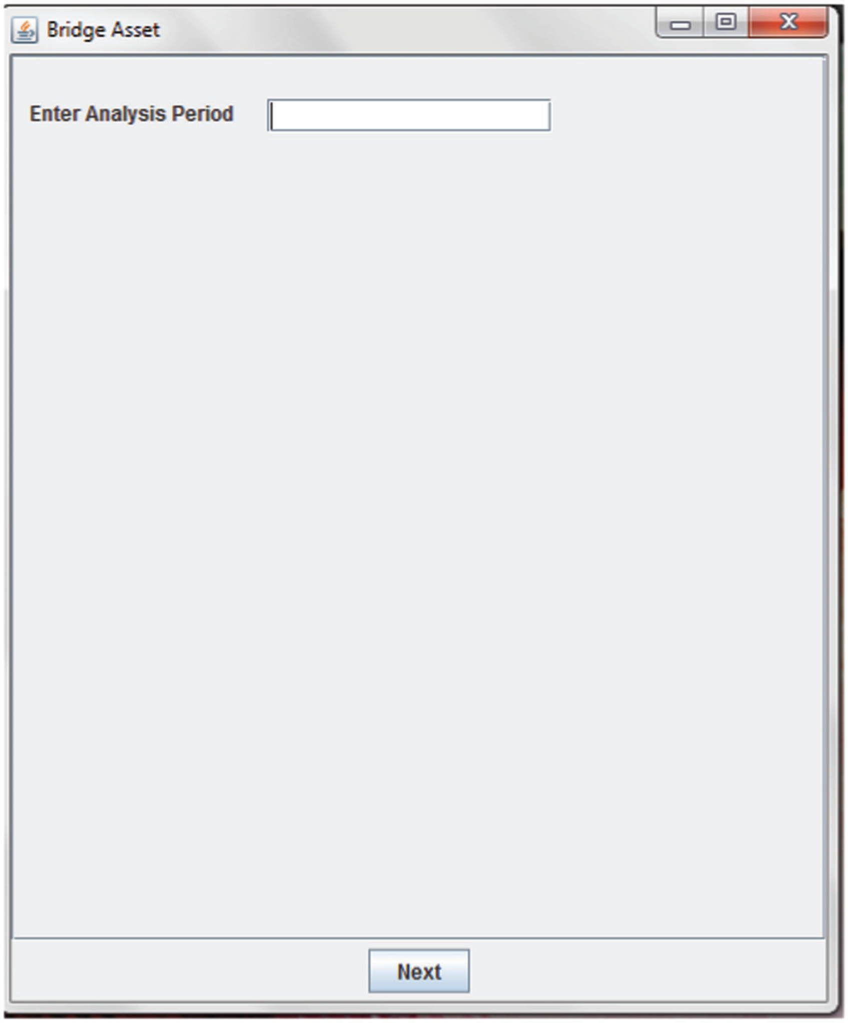


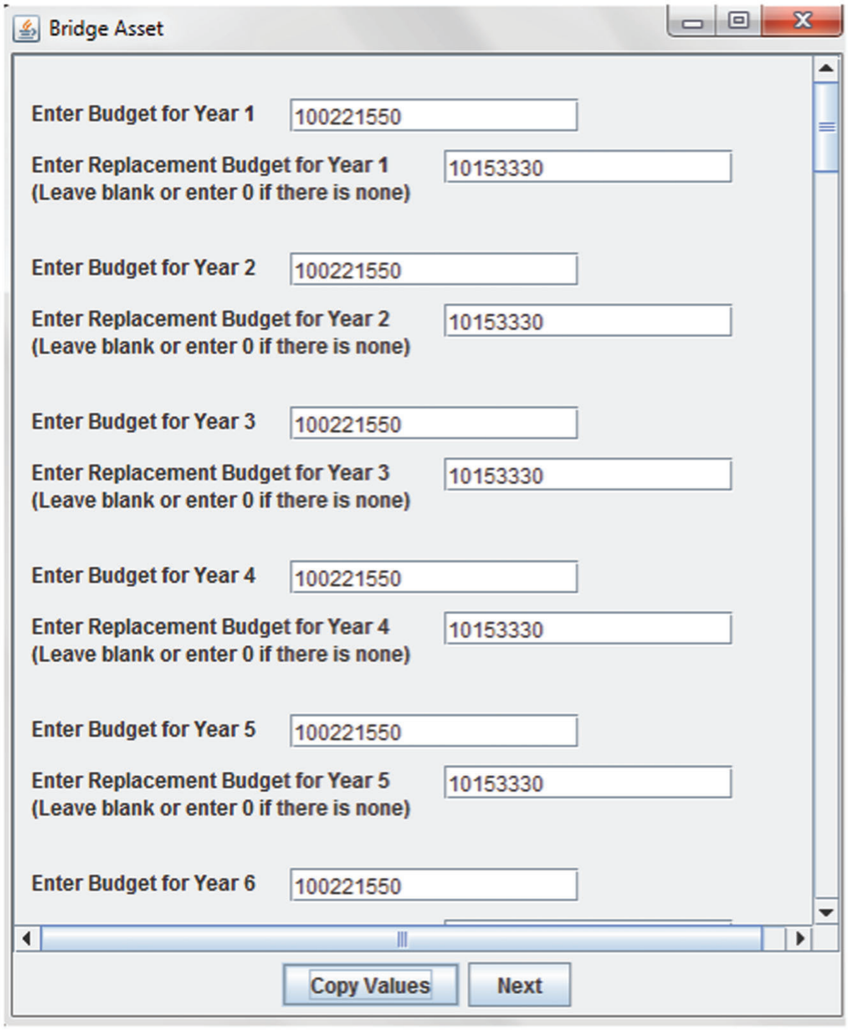
Figure 3.4 Analysis period input screen.

candidate for substructure treatment. Because BMRS compares bridge maintenance treatments by component instead of by bridge; BMRS must compare projects between components. To do this, BMRS will choose the lowest overall component rating. Continuing with the same example, BMRS will sort the bridge components in the following order: 2, 3, 4, 5, 5, 6, 6, and 7. For these four bridges, BMRS will sort them in the following order for treatment: 33175 substructure; 33174 deck; 23305 substructure; 23305 deck and 33174 substructure; 26850 deck and 26850 substructure; and 33175 deck. It is important to note that when condition rating is equal, BMRS will select the first project entered into BMRS (of the projects with equal ratings). For example, because 23305 deck and 33174 substructure have equal ratings, BMRS will rank 23305 deck ahead of 33174 substructure; even though the two components have equal condition ratings. 23305 deck is ranked ahead of 33174 substructure only because it was entered first.

BMRS uses a merge sorting algorithm (Grama, 2013). A merge sorting algorithm is a multi-stage sorting algorithm. A merge sorting algorithm first takes a set of data and divides it into smaller subsets of data. The merge sort then takes each subset and sorts that subset in the desired order. Once all the subsets of data have been sorted, the subsets are merged into larger subsets. These subsets are again sorted. This process of sorting subsets, merging smaller subsets into larger subsets and sorting those larger subsets is repeated until the original set of data has been sorted.

BMRS uses a merge sorting process to sort every bridge component from the worst condition rating to the best condition rating. BMRS starts with a condition rating for every bridge component. This set of ratings is then broken into subsets with only some of the condition ratings. These subsets are sorted and merged into larger subsets. BMRS repeats this sorting and merging process until every bridge component has been sorted from worst to best condition rating.

Once BMRS has sorted all the bridge components by condition rating, treatments will be selected for the first year of the analysis period. The bridge components with the lowest (worst) condition ratings will be the first



Enter Budget for Year 1: 100221550
Enter Replacement Budget for Year 1 (Leave blank or enter 0 if there is none): 10153330
Enter Budget for Year 2: 100221550
Enter Replacement Budget for Year 2 (Leave blank or enter 0 if there is none): 10153330
Enter Budget for Year 3: 100221550
Enter Replacement Budget for Year 3 (Leave blank or enter 0 if there is none): 10153330
Enter Budget for Year 4: 100221550
Enter Replacement Budget for Year 4 (Leave blank or enter 0 if there is none): 10153330
Enter Budget for Year 5: 100221550
Enter Replacement Budget for Year 5 (Leave blank or enter 0 if there is none): 10153330
Enter Budget for Year 6: 100221550

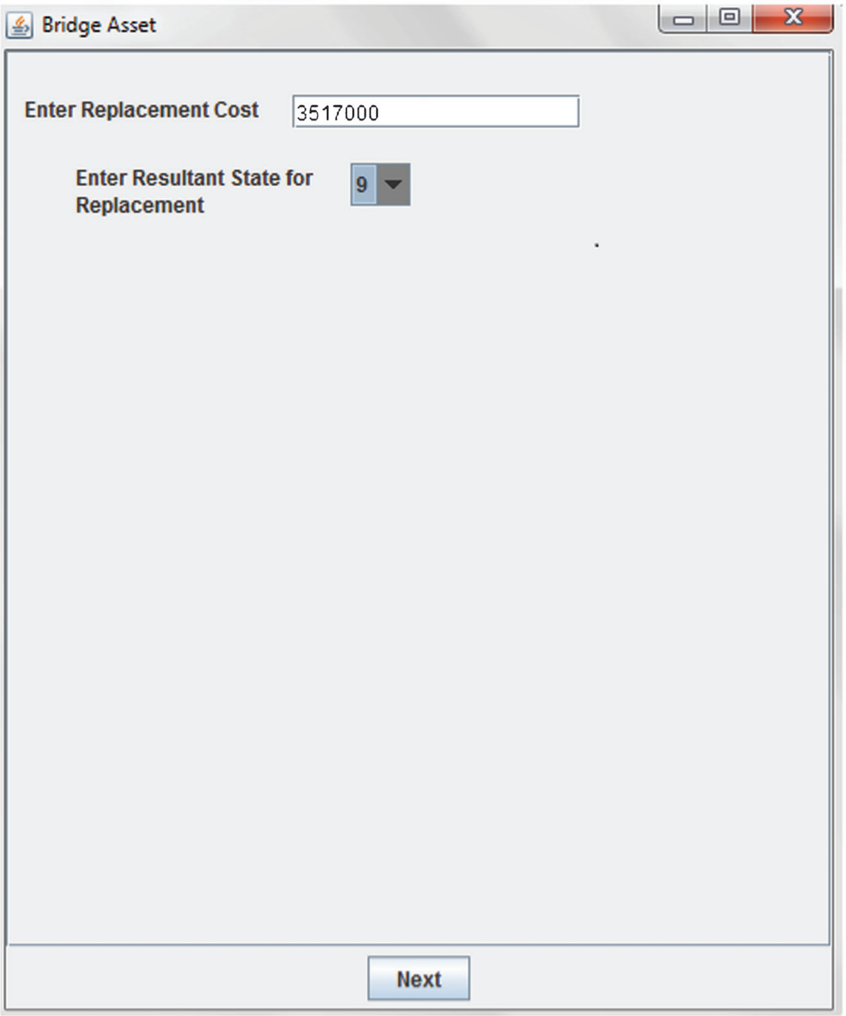
Figure 3.5 BMRS budget input screen.

to get treatments applied to them. To select which treatment will be applied, BMRS will find all the treatments where the component's condition rating falls between the treatment's upper and lower bound (see Figures 3.8 and 3.9). A treatment cannot be applied to a bridge component outside of the boundary condition ratings for that treatment. For example, if a bridge deck has a condition rating of 2, and a deck treatment has a lower bound of 1 and an upper bound of 4, this treatment will be considered for use on the bridge deck. However if a deck treatment has a lower bound of 3 and an upper bound of 5, it will not be considered for use on a bridge deck with a condition rating of 2; because the condition rating for this treatment is outside of the boundary condition ratings. Figures 3.8 and 3.9 show an example of these two deck treatments.

For each treatment, all bridge components that have a condition rating outside of the treatment's boundary condition ratings will not get that treatment assigned as a possible treatment to be performed. Once all possible treatments have been determined for a bridge component, only one treatment will be selected. It is possible that a bridge component can have a condition rating that will fall between the upper and lower bound of more than one treatment type. In this case the treatment with the higher lower bound will be chosen. BMRS makes the assumption that treatments with larger lower bounds are not as intensive in terms of agency cost and user cost as treatments with smaller lower bounds. For example, BMRS assumes that a deck resurfacing treatment is not as costly as a treatment like a deck replacement. If a bridge would have a condition rating that could trigger

TABLE 3.1
BMRS budget items and treatments (Sinha et al., 2009)

Treatment	Treatment code	Budget item
Bridge Replacement	14	Replacement Budget
Deck Rehabilitation	01	Maintenance Budget
Deck Replacement	3	Maintenance Budget
Substructure Rehabilitation	16	Maintenance Budget
Superstructure Strengthening	12	Maintenance Budget
Superstructure Replacement	10	Maintenance Budget



Enter Replacement Cost 3517000

Enter Resultant State for Replacement 9

Figure 3.6 BMRS replacement treatment screen.

either of these treatments, BMRS would choose the deck resurfacing treatment to apply to the bridge deck.

Once a treatment is applied to the first bridge component on the sorted list, BMRS deducts the treatment cost from the budget. BMRS then repeats the process of finding a treatment to apply to the next bridge component on the sorted list. Treatments are applied until the given budget runs out for the first year.

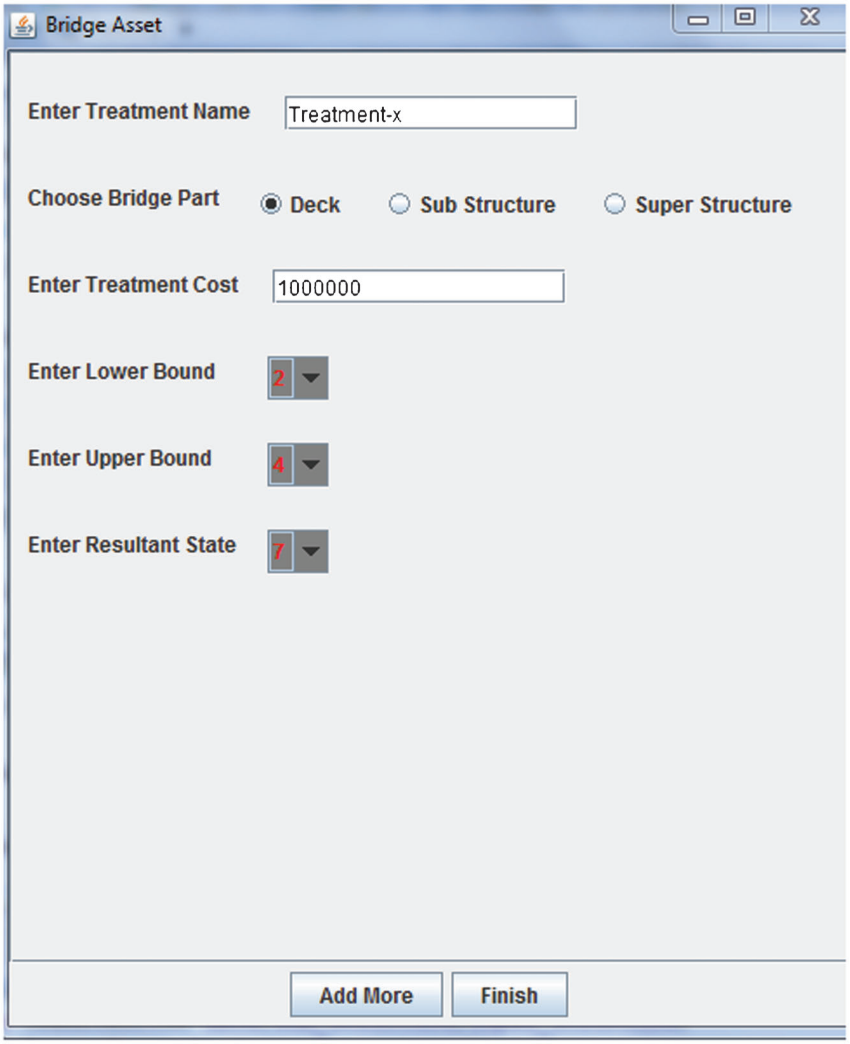
Bridge components that are treated in a given year get a "performance jump" in that year based on the treatment applied (see Figure 3.10). This performance jump varies by treatment, and can be set by the BMRS user. Figure 3.10 shows an example of a treatment with a performance jump that could be created by a BMRS user. For this example treatment, a performance jump occurs at year 20 in a 25-year analysis period. The bridge has an initial component condition rating of 4 in year 0, the start of the analysis period. The bridge deteriorates until year 20, when it is treated and experiences a performance jump to a rating of 7.

Bridge components that are not treated will experience deterioration due to factors such as traffic loading and weather conditions. BMRS uses deterioration models that were developed for IBMS (Sinha et al., 2009). Equations 3.1 through 3.3 show the deterioration models used by BMRS.

$$\text{Deck Condition Rating Deterioration} = 3.588 + \frac{133.641}{27.399 + (0.000128 * year)^{3.322}} \tag{3.1}$$

This formula was developed for concrete bridge decks. The formula used by BMRS is the corrected version of the formula given in the report for project SPR-3013: *Updating and Enhancing the Indiana Bridge Management System*. In that report, the formula is incorrectly written as $DCR=3.588-(133.641/(27.399+0.000128*year^{3.322}))$. Additionally, the report's accompanying graph is incorrectly representing the deterioration of a bridge from a condition rating of 9, instead of the correct value of 8.5. Once the formula is corrected to the version given in Equation 3.1, the results align perfectly with the given graph.

A similar formula is available for steel bridge decks. However, at this time, BMRS only considers concrete bridge decks in its analysis. This is because concrete



Enter Treatment Name: Treatment-x

Choose Bridge Part: ● Deck ○ Sub Structure ○ Super Structure

Enter Treatment Cost: 1000000

Enter Lower Bound: 2

Enter Upper Bound: 4

Enter Resultant State: 7

Figure 3.7 Bridge treatment input screen.

bridge decks are much more common than steel bridge decks in Indiana. Future researchers may choose to modify the BMRS code to add a deterioration formula for steel bridge decks or decks made of other materials.

$$\text{Superstructure Condition Rating Deterioration} = 2.1032 + \frac{19.217}{2.7996 + (0.000386 * year)^{2.2320}} \quad (3.2)$$

TABLE 3.2
BMRS sorting example

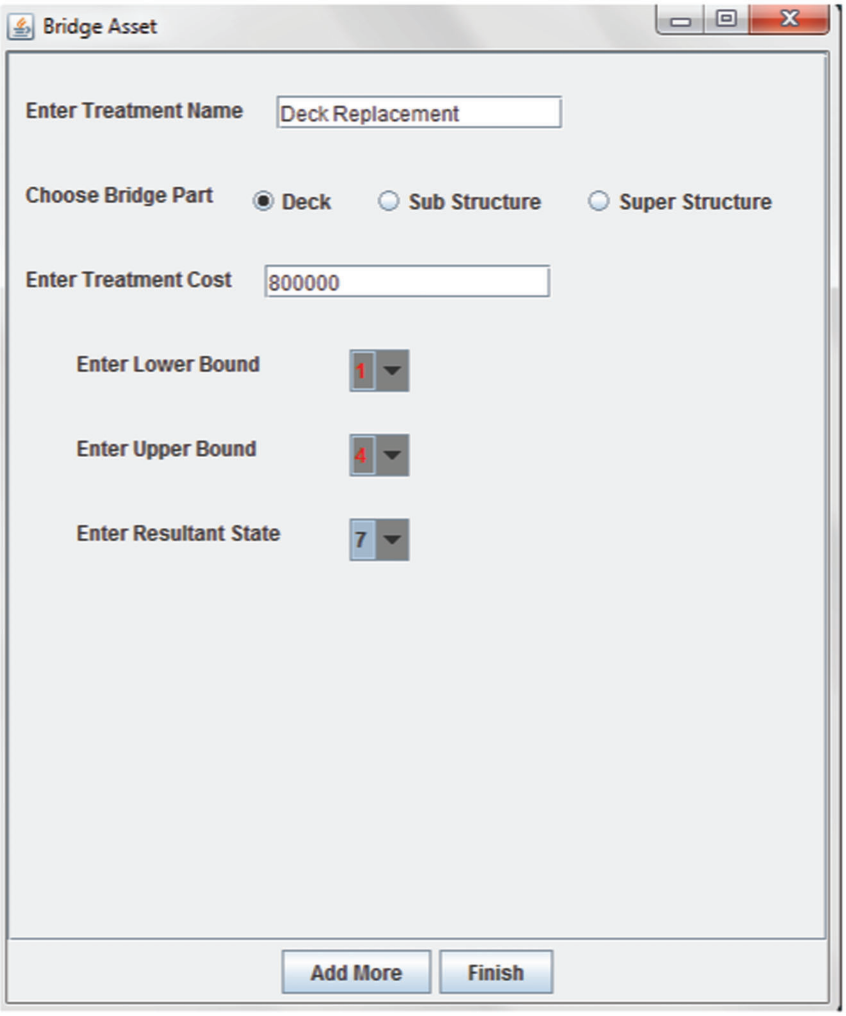
Bridge number	Deck condition rating	Substructure condition rating
23305	5	4
33174	3	5
33175	7	2
26850	6	6

This formula was developed for concrete bridge superstructure. A similar formula is available for steel superstructures; however, BMRS is only able to analyze concrete bridge superstructures at this time. Future researchers may choose to modify the BMRS code to add a deterioration formula for steel superstructures.

$$\text{Substructure Condition Rating Deterioration} = 2.68044 + \frac{24.9488}{3.94916 + (0.00038 * year)^{2.27543}} \quad (3.3)$$

The formula for substructure deterioration is the same for all bridge types, regardless of the material the substructure is made of (Sinha et al., 2009).

To find the deterioration that a bridge will experience in a year, BMRS starts by assuming the superstructure or substructure component had a rating of 9 and the deck had a rating of 8.5 in year 0. Using this assumption, BMRS first calculates current year condition ratings based on the age of the components; the age is 0 in year 0. Then, BMRS calculates the next



Enter Treatment Name: Deck Replacement

Choose Bridge Part: ● Deck ○ Sub Structure ○ Super Structure

Enter Treatment Cost: 800000

Enter Lower Bound: 1

Enter Upper Bound: 4

Enter Resultant State: 7

Figure 3.8 Deck replacement (example treatment 1).

year's condition ratings, also based on the age (which would now be one year greater). Finally, the difference between the two previously calculated ratings is taken as the deterioration that will occur between a current year and the next year. Table 3.3 shows an example of how BMRS calculates this deterioration for a bridge deck with a condition rating of 6 that has not been treated for 20 years. (The new condition rating will apply to the substructure in year 21.)

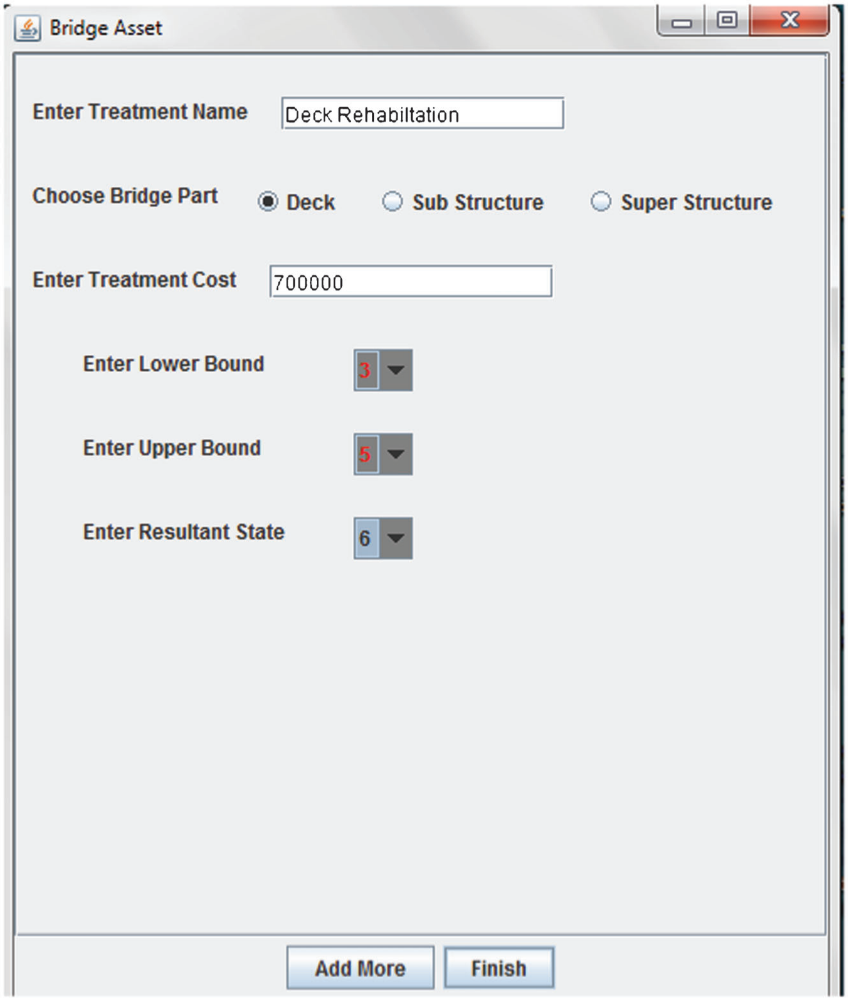
The following steps are used to calculate the deterioration for a bridge component.

(1) Calculate the component condition in year 20 using formula given in Equation 3.1: 3.588+(133.641/(27.399+0.000128*20ˆ3.322))=8.029999.
(2) Calculate the component condition in year 21 using formula given in Equation 3.1: 3.588+(133.641/(27.399+0.000128*21ˆ3.322))=7.96128.
(3) Calculate the difference in these two conditions is calculated using simple subtraction: year 20 rating- year 21 rating=8.029999−7.96128=0.06872.
(4) Calculate the new component condition rating for year 21 is using the current condition rating: current condition rating - difference in condition =6−0.06872=5.93128.

Once BMRS has completed the process of updating the bridge component condition ratings in a given year, BMRS repeats the process of selecting treatments for bridge components for the next year. The bridge components that are treated receive a performance jump, and the condition of all untreated bridge components deteriorates based on the previously discussed formulas. BMRS continues the process of selecting treatments for a given year and then updating component condition ratings until the analysis period has been completed. Table 3.4 gives an example of how BMRS will calculate deterioration for an untreated bridge during a 3-year analysis period.

3.4. Using BMRS to Test Trigger Value Scenarios

Although the original intent of this project was to use IBMS to perform the trigger value analysis discussed in Chapter 1, an alternative had to be found to perform the analysis when IBMS did not work correctly. BMRS was developed as an alternative to IBMS to allow the analyses needed for the research. The steps used to set up the analysis are discussed in this section.



Enter Treatment Name: Deck Rehabiltation

Choose Bridge Part: ● Deck ○ Sub Structure ○ Super Structure

Enter Treatment Cost: 700000

Enter Lower Bound: 3

Enter Upper Bound: 5

Enter Resultant State: 6

Figure 3.9 Deck rehabilitation (example treatment 2).

The first part of testing trigger value scenarios was to construct an input file, as discussed in Section 2 of this chapter. The input file was constructed from data retrieved from the BridgeInspectTech system used by INDOT. The data set contains only the concrete bridges in the Indiana bridge network. The file was in an .xls format, with column headings shown in Figures 3.2 and 3.3.

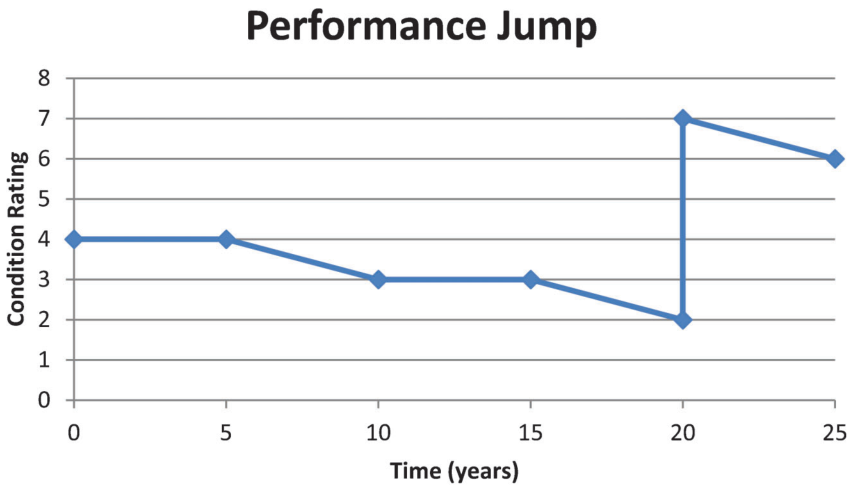


Figure 3.10 Example performance jump for 25-year analysis.

TABLE 3.3
BMRS deterioration example

Years since treatment	Deterioration amount	Previous year condition rating	New condition rating
20	0.06872	6	5.93128

The second part of testing trigger values was to select an analysis period. A 50-year analysis period was selected for all trigger value scenarios. The trigger value scenarios are given in Tables 3.5 through 3.7.

The next part of testing trigger value scenarios was to input the budget. Three different budget scenarios were chosen for this project. All three scenarios involve a constant budget level. Levels of $150 million per year; $200 million per year; or $250 million per year were chosen for all trigger value scenarios. Bridges with a higher traffic volume experience deterioration more quickly than lower traffic volume bridges because of the increased loading produced by having more traffic. This means that, in a real system, a bridge management program will perform maintenance operations on these higher traffic volume bridges more frequently than lower traffic volume bridges. To model that higher traffic volume bridges have maintenance performed on them more frequently, BMRS assigns a larger percentage of the budget to bridges with higher traffic volumes. BMRS uses three categories of traffic volumes, based on the ADT level of bridges.

In the programming for IBMS, 12 functional class codes that were used (Sinha et al., 2009). Because BMRS seeks to approximate IBMS results, the funding levels were divided up for this project based on the functional classes used by IBMS. The three categories of traffic volumes are given in Table 3.8.

Table 3.9 shows the percentage of bridges in each category, while Table 3.10 shows the percentage of ADT that travels on the bridges in each category.

To divide up the budget to each category, the 20.31% of the annual budget that is used on widening and replacement costs is first removed. The rest of the budget is divided up based on the percentage of bridges in each category and the percentage of ADT in each category. This is done using Equation 3.4.

$$\text{Remaining Budget} = 0.5 * \text{Percent\_Bridge} + 0.5 * \text{Percent\_ADT} \tag{3.4}$$

In this formula, the variable B is the percentage of the budget that is assigned to a category. The variable Percent_Bridges is the percentage of bridges in a category. The variable Percent_ADT is the percentage of ADT in a category. The following example shows how this formula is used: For the category ADT≥5000, B=0.5*70.52591+ 0.5*97.15276=83.8393354. This means that 83.84% of the remaining budget will be assigned to bridges with an ADT greater than 5000. Table 3.11 shows the results of using formula 3.4 for each budget level.

The values given in Table 3.11 represent only the maintenance budget. The replacement budget values are applied separately and replacement treatments are performed before any of the maintenance treatments are performed. Table 3.12 gives these values.

For each replacement budget level, a third of the overall replacement budget amount was assigned to each ADT category. This is a different method than the one used to assign a percentage of the maintenance budget to an ADT category. Replacement treatments have a higher treatment cost than maintenance treatments. If too small a budget is given to an ADT category, replacement treatments cannot be performed. Because replacement treatments are performed on the bridges that are in the worst condition, if no replacement treatments are performed on an ADT category, bridges in that category may become dangerous for users. By assigning enough of the overall budget to each ADT category; it guarantees that the worst bridges in each ADT category can be replaced. By giving equal replacement budget to lower ADT categories, it will help to offset the fact that fewer maintenance treatments can be performed on the lower ADT categories because of the smaller budget.

Several different treatment types were used in the analysis of trigger value scenarios. For each budget level, the trigger values will be varied in the same manner. The first set of trigger values for lower and upper bounds for these treatments will be the control set of trigger values. Subsequent sets of trigger values will be tested after the results from the standard maintenance strategy are established. The results from these subsequent sets of trigger values will be compared to the results from the standard maintenance strategy. Figures 3.11 through 3.15 show the treatment types

TABLE 3.4
Example BMRS deterioration calculation for untreated bridge (3 year analysis period)

Year	Structure number	Overall deck rating	Overall substructure rating	Overall superstructure rating
Starting Condition	23305	6	7	7
Year 1	23305	5.931280459	6.945458426	6.930034876
Year 2	23305	5.856997951	6.888612771	6.857551539
Year 3	23305	5.777352621	6.829587009	6.78274043

TABLE 3.5
Trigger values of treatments for standard maintenance strategy run

Run	Treatment name	Lower bound	Upper bound
Standard maintenance strategy	Deck Rehabilitation	3	5
	Deck Replacement	1	3
	Substructure Rehabilitation	1	5
	Superstructure Strengthening	3	5
	Superstructure Replacement	1	3

TABLE 3.6
Trigger values of treatments for early maintenance run

Run	Treatment name	Lower bound	Upper bound
Early maintenance	Deck Rehabilitation	4	6
	Deck Replacement	1	4
	Substructure Rehabilitation	1	6
	Superstructure Strengthening	4	6
	Superstructure Replacement	1	4

TABLE 3.7
Trigger values of treatments for late maintenance run

Run	Treatment name	Lower bound	Upper bound
Late maintenance	Deck Rehabilitation	2	4
	Deck Replacement	1	2
	Substructure Rehabilitation	1	4
	Superstructure Strengthening	2	4
	Superstructure Replacement	1	2

TABLE 3.8
Functional class Categories and Corresponding Functional classes

Category	Functional classes	Functional class codes
ADT≥5000	Rural Interstate, Urban Interstate, Expressways, Rural Principal Arterials, Urban Principal Arterials, Rural Minor Arterials, Urban Minor Arterials, Rural Major Collectors, Rural Minor Arterials	1, 2, 6, 7, 11, 12, 14, 16
5000>ADT≥750	Rural Minor Collectors (Non-NHS, Minor), Urban Collectors	8, 17
750>ADT	Rural Minor Collectors (Non-NHS Local), Rural Local, Urban Local	8, 9, 19

TABLE 3.9
Percentage of bridges in each category

Category	Number of bridges	Percentage of bridges
ADT≥5000	3661	70.52591
5000>ADT≥750	1218	23.46369
750>ADT	312	6.01040

TABLE 3.10
Percentage of ADT in each category

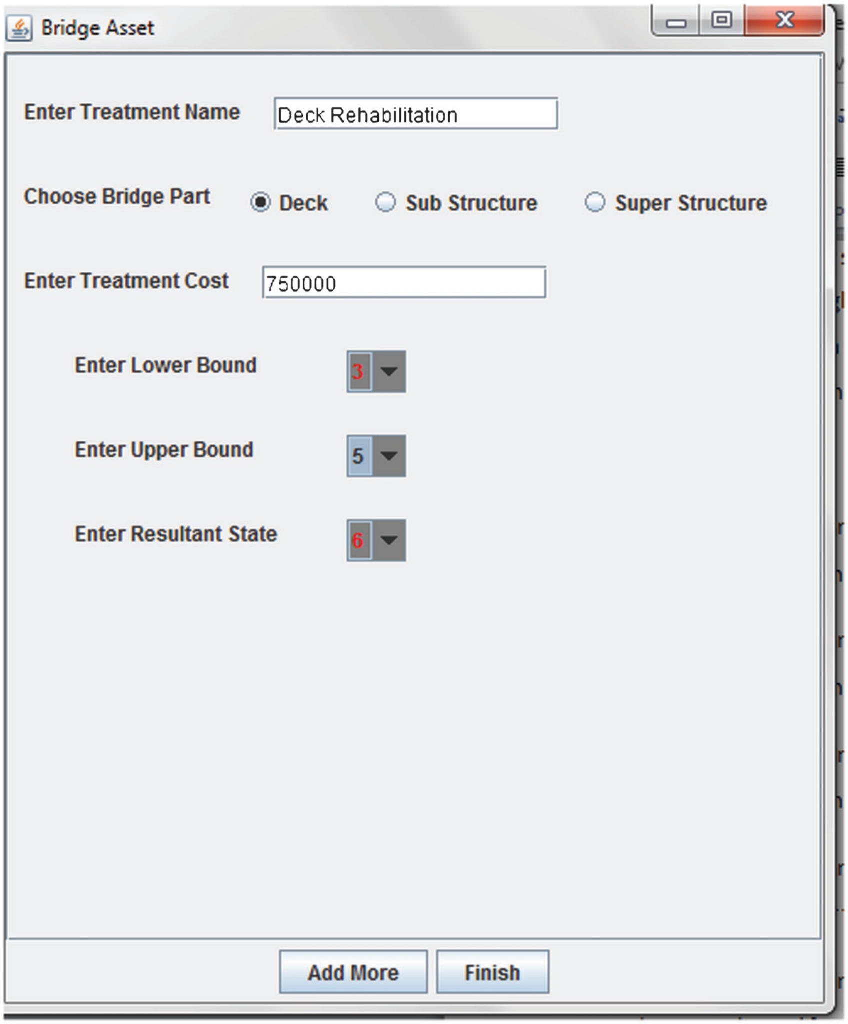
Category	Percentage of ADT
ADT≥5000	97.15276
5000>ADT≥750	2.75317
750>ADT	0.09407

TABLE 3.11
Amount of maintenance budget assigned to each ADT category

Budget level	ADT category	Percentage of budget	Budget amount assigned
150,000,000	ADT≥5000	83.83933538	100,221,550
150,000,000	5000>ADT≥750	13.10842957	15,669,818
150,000,000	750>ADT	3.052235053	3,648,642
200,000,000	ADT≥5000	83.83933538	133,628,733
200,000,000	5000>ADT≥750	13.10842957	20,893,091
200,000,000	750>ADT	3.052235053	4,864,856
250,000,000	ADT≥5000	83.83933538	167,035,916
250,000,000	5000>ADT≥750	13.10842957	26,116,363
250,000,000	750>ADT	3.052235053	6,081,070

TABLE 3.12
Amount of replacement budget assigned to each ADT category

Budget level	ADT category	Budget amount assigned
150,000,000	ADT≥5000	10,153,330
150,000,000	5000>ADT≥750	10,153,330
150,000,000	750>ADT	10,153,330
200,000,000	ADT≥5000	13,537,773
200,000,000	5000>ADT≥750	13,537,773
200,000,000	750>ADT	13,537,773
250,000,000	ADT≥5000	16,922,216
250,000,000	5000>ADT≥750	16,922,216
250,000,000	750>ADT	16,922,216



Enter Treatment Name: Deck Rehabilitation

Choose Bridge Part ● Deck ○ Sub Structure ○ Super Structure

Enter Treatment Cost: 750000

Enter Lower Bound: 3

Enter Upper Bound: 5

Enter Resultant State: 6

Figure 3.11 Deck rehabilitation treatment.

that were used by BMRS in the analysis. The trigger values shown in these figures are for the standard maintenance strategy. Tables 3.5 through 3.7 show the different sets of trigger values that are used for the different strategies.

The costs shown in Figures 3.11 through 3.15 were calculated from a run of dTIMS performed by INDOT for this project. The costs displayed in these figures are average costs for all sizes of bridges. In a real situation, economies of scale would make the costs different, based on the square footage of each bridge. However, insufficient data are available to calculate costs in this way. An average cost was used in an attempt to minimize the error given from ignoring economies of scale. However, the set of treatments used do not take widening and replacement costs into account. Based on the dTIMS run performed by INDOT for this project, 20.31% of the bridge budget was spent annually on projects that involve bridge widening or replacement. To account for this, 20.31% of the annual budget was removed from each trigger value scenario and put into the replacement cost budget.

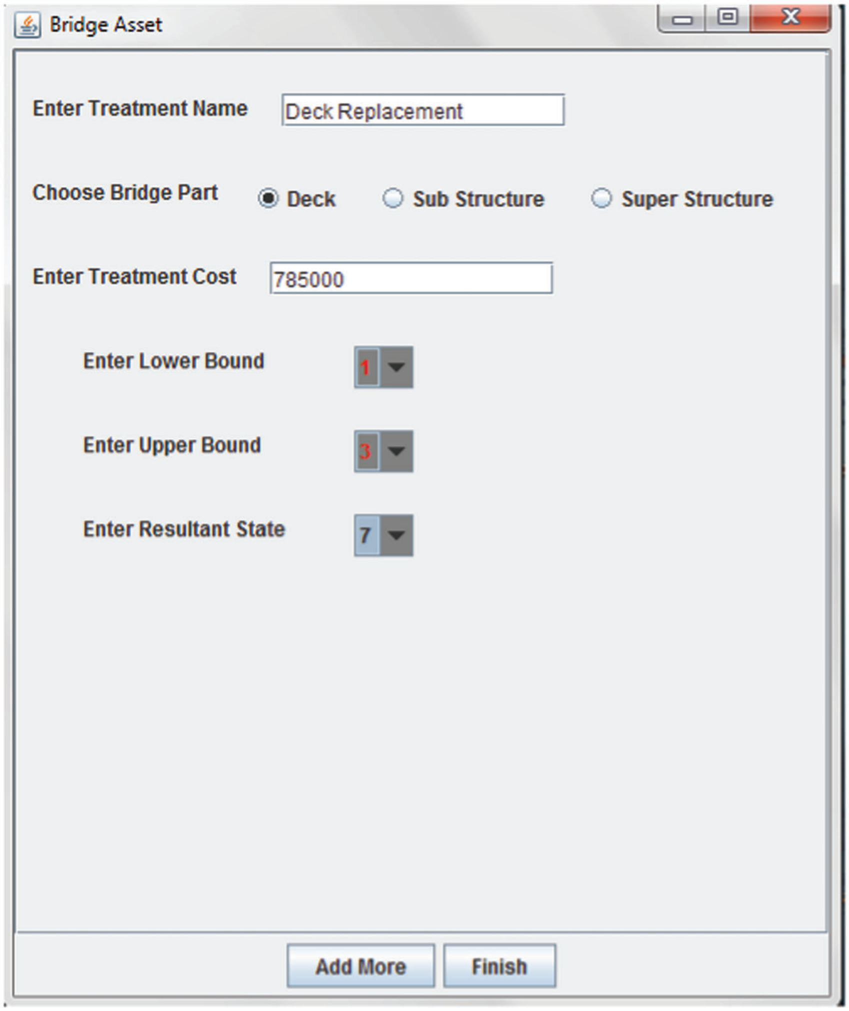
The treatment shown in Figure 3.11 is a bridge deck rehabilitation. The lower bound for this treatment is 3.The upper bound for this treatment is 5. The resultant state for this treatment is 6.

The treatment shown in Figure 3.12 is a bridge deck replacement. The lower bound for this treatment is 1. The upper bound for this treatment is 3. The resultant state for this treatment is 7.

The treatment shown in Figure 3.13 is a substructure rehabilitation. The lower bound for this treatment is 1.The upper bound for this treatment is 5. The resultant state for this treatment is 6.

The treatment shown in Figure 3.14 is a superstructure strengthening. The lower bound for this treatment is 3. The upper bound for this treatment is 5. The resultant state for this treatment is 6.

The treatment shown in Figure 3.15 is a superstructure replacement. The lower bound for this



Enter Treatment Name: Deck Replacement

Choose Bridge Part: ● Deck ○ Sub Structure ○ Super Structure

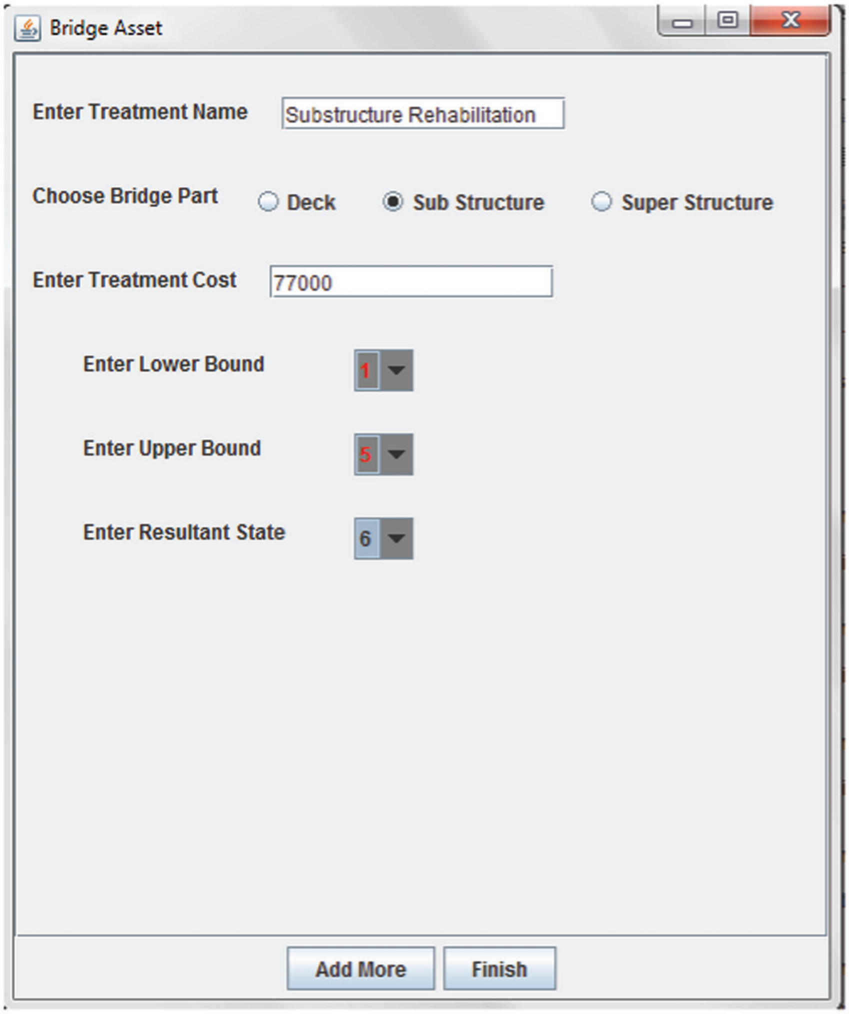
Enter Treatment Cost: 785000

Enter Lower Bound: 1

Enter Upper Bound: 3

Enter Resultant State: 7

Figure 3.12 Deck replacement treatment.



Enter Treatment Name: Substructure Rehabilitation

Choose Bridge Part: ○ Deck ● Sub Structure ○ Super Structure

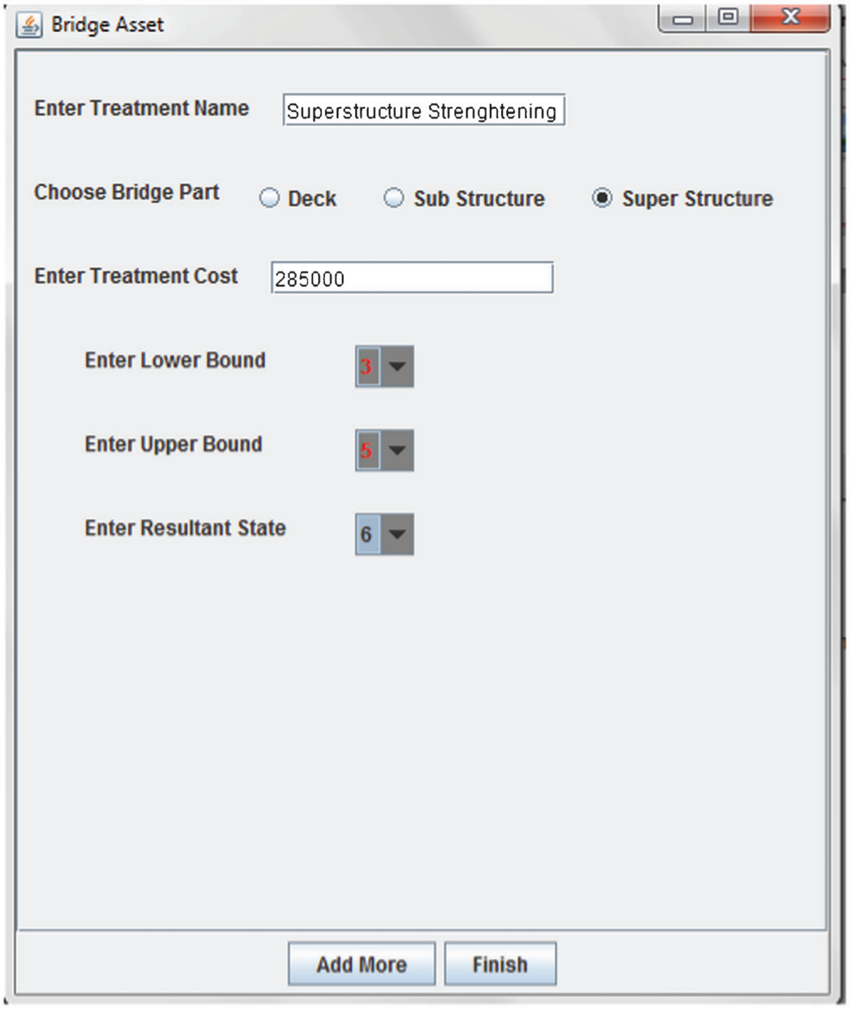
Enter Treatment Cost: 77000

Enter Lower Bound: 1

Enter Upper Bound: 5

Enter Resultant State: 6

Figure 3.13 Substructure rehabilitation treatment.



Enter Treatment Name: Superstructure Strenghtening

Choose Bridge Part: ○ Deck ○ Sub Structure ● Super Structure

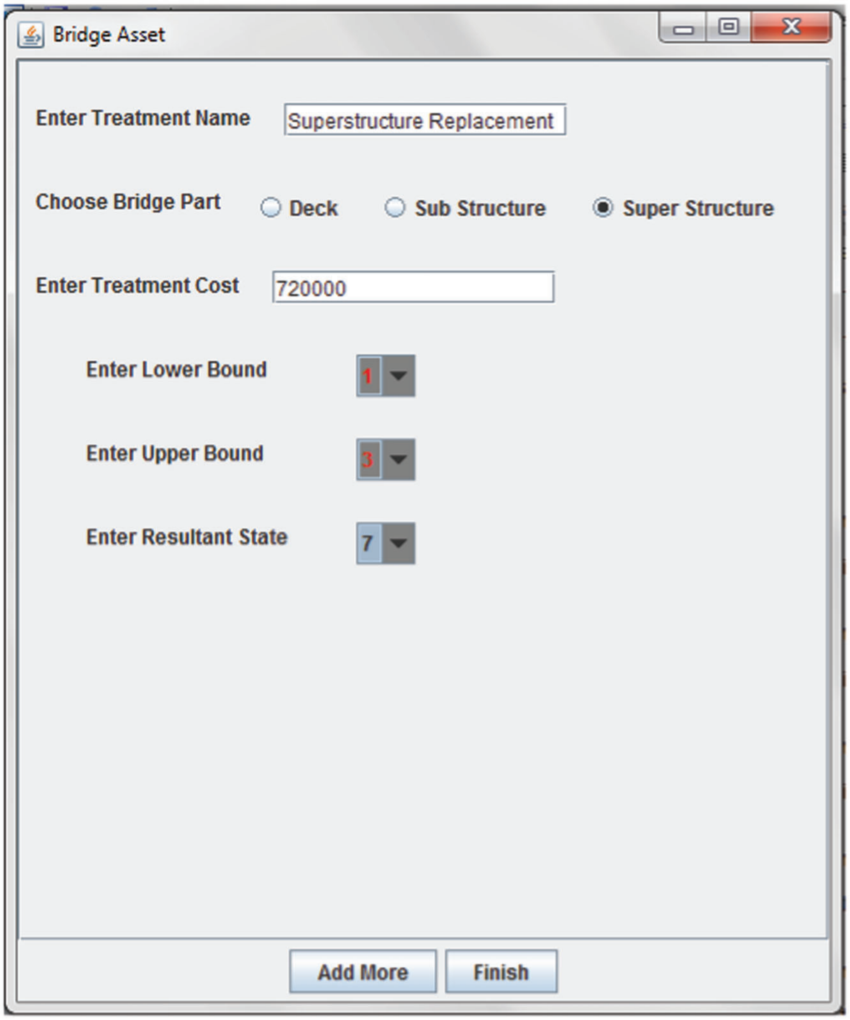
Enter Treatment Cost: 285000

Enter Lower Bound: 3

Enter Upper Bound: 5

Enter Resultant State: 6

Figure 3.14 Superstructure strengthening treatment.



Enter Treatment Name: Superstructure Replacement

Choose Bridge Part: ○ Deck ○ Sub Structure ● Super Structure

Enter Treatment Cost: 720000

Enter Lower Bound: 1

Enter Upper Bound: 3

Enter Resultant State: 7

Figure 3.15 Superstructure replacement treatment.

treatment is 1. The upper bound for this treatment is 3. The resultant state for this treatment is 7.

4. ANALYZING BMRS RESULTS

4.1. Distribution Analysis

It is helpful to see the distribution of component condition ratings at the initial state of the bridge network, before BMRS performs any analysis. This distribution will provide a snapshot of component conditions for the entire bridge network. High component condition ratings indicate a healthy bridge network. Low component condition ratings indicate an unhealthy bridge network in need of increased maintenance. The initial distribution of the component condition ratings can be compared to the distribution of component condition ratings after BMRS implements particular bridge management strategies with specified budgets. By comparing these distributions, the effectiveness of different maintenance budgets and plans can be analyzed. Figures 4.1, 4.5, and 4.9 show the initial distributions of component condition ratings for each bridge component. These distributions are presented as histograms. For all histograms in this chapter, the label for the condition rating bin represents the upper bound of the bin. For example, the bin labeled 5 contains all the bridges with a condition rating between 4 and 5.

The initial component condition rating for bridge decks indicates that, overall, the bridge decks in the bridge network are in adequate condition. The majority of bridge decks have a condition rating of 5 or greater. Because 5 is considered fair condition, this means that the majority of bridge decks are in at least fair condition. Only a few bridge decks have a condition rating of 3 or lower. A rating of 3 is considered to be poor condition, requiring that maintenance or replacement be performed soon.

Figures 4.2 through 4.4 show the distributions of deck condition ratings after BMRS performs analysis for each budget level. These distributions are presented as histograms. For the histograms in this chapter, the label for the condition rating bin represents the upper bound of the bin. For example, the bin labeled 5 contains all the bridge components with a condition rating between 4 and 5. Although component condition ratings are integer values, because they are being calculated with a deterioration model, decimal values are possible in the model.

With a $150 million budget, the standard maintenance strategy has the greatest number of bridge decks with a condition rating above 5. The majority of these decks have a rating between 5 and 6, as shown by the high value in the condition rating bin labeled "6." The early maintenance strategy has the greatest number of bridge decks with a condition rating of 6 or greater. This shows that the early maintenance strategy leads to a trade-off between quantity and quality. Although the early maintenance strategy has fewer bridge decks with a condition rating above 5 than the standard maintenance strategy does, it also has more bridge decks with ratings above 6. These bridge decks will take longer to deteriorate to the lower condition ratings, so they will have slightly longer before they must be

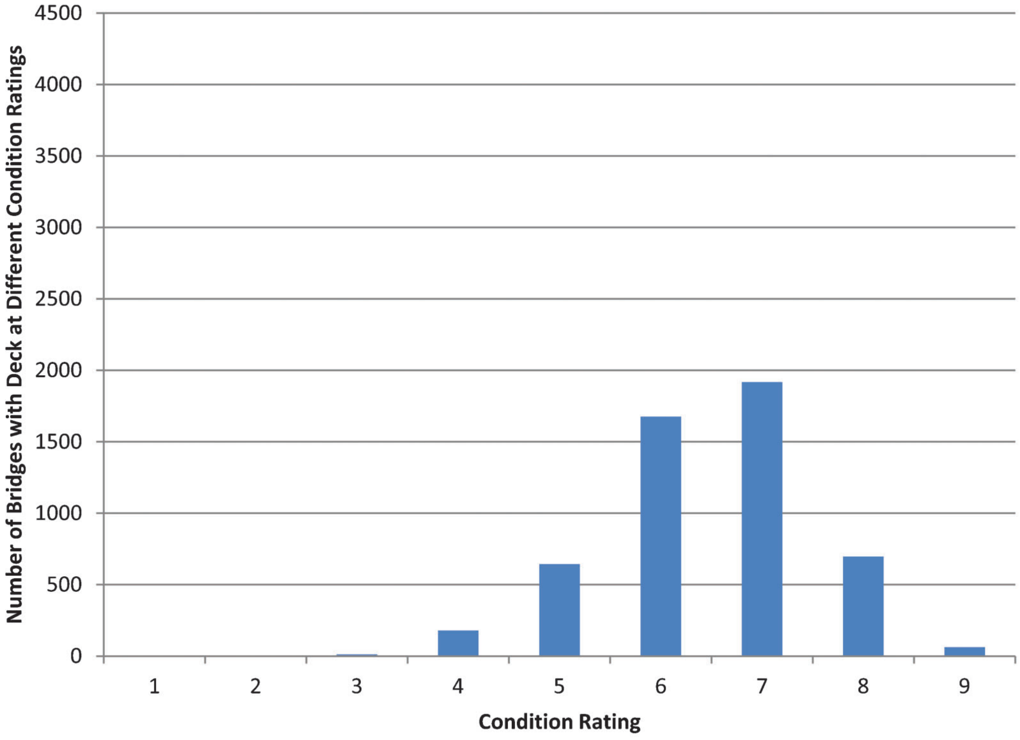


Figure 4.1 Initial deck condition rating distribution.

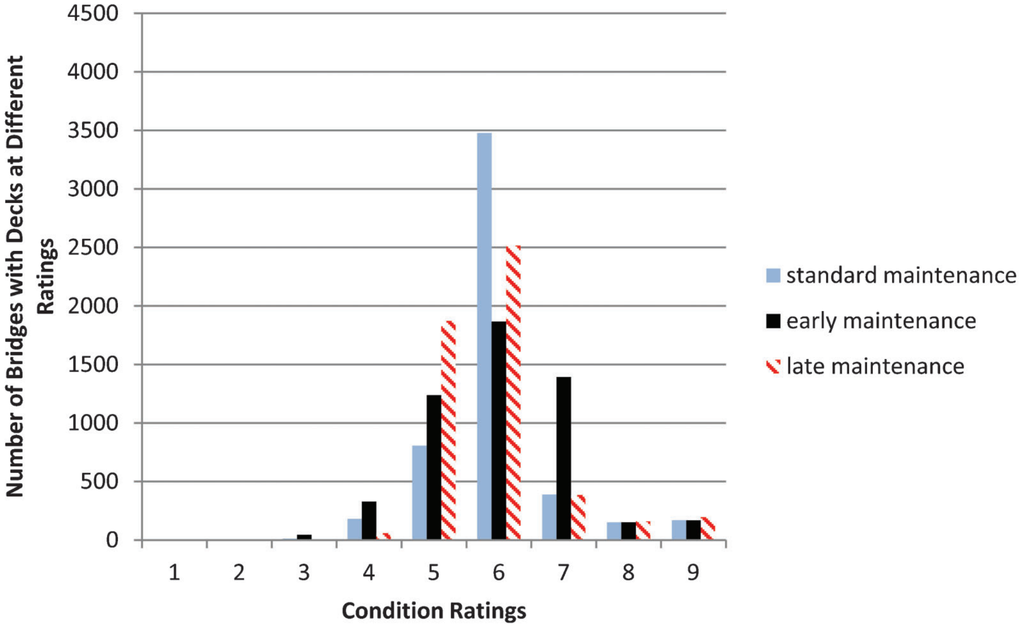


Figure 4.2 Deck condition rating distribution after BMRS run for $150 million budget.

replaced or have maintenance performed on them. The late maintenance strategy has the fewest bridge decks with a condition rating below 5, and the greatest number of bridge decks with a condition rating between 4 and 5. This shows that the late maintenance strategy has the fewest bridge decks in inadequate condition.

For a $200 million budget, the standard maintenance strategy has the greatest number of bridge decks with a condition rating above 5. The early maintenance strategy has the greatest number of bridge decks with a condition rating of 6 or greater. This shows that the early maintenance strategy provides a trade-off between quantity and quality. Although the early maintenance strategy has fewer bridge decks with a condition rating above 5 than the standard maintenance strategy does, it also has more bridge decks with ratings above 6. The late maintenance strategy has the fewest bridge decks with a condition rating below 5, but the greatest number of bridge decks with a condition rating between 4 and 5. The $200 million budget also has fewer bridge decks with condition ratings of 3 or lower and more bridge decks with a condition rating of 5 or greater than

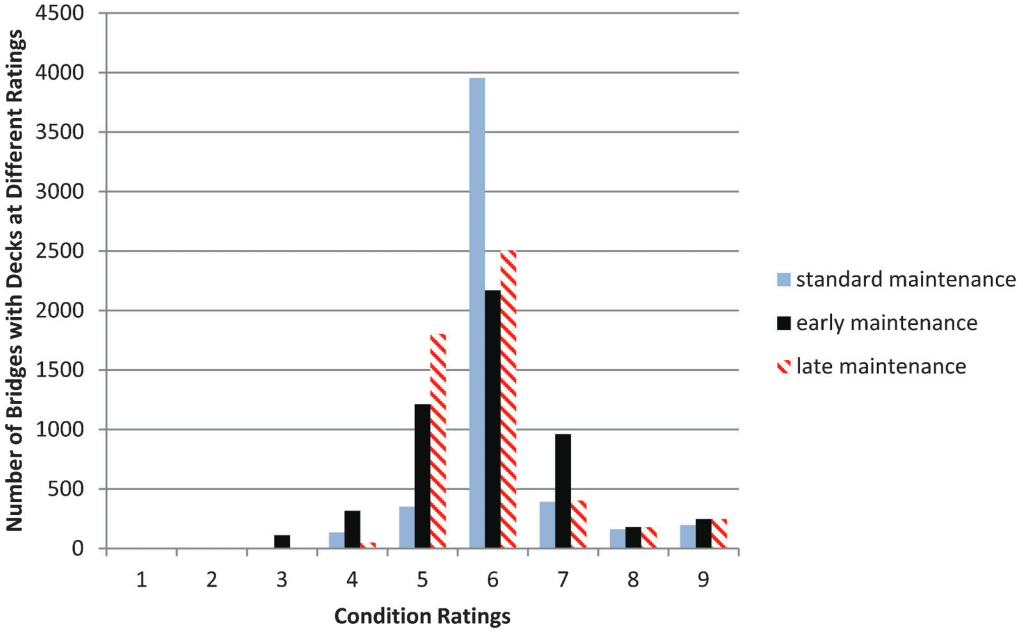


Figure 4.3 Deck condition rating distribution after BMRS run for $200 million budget.

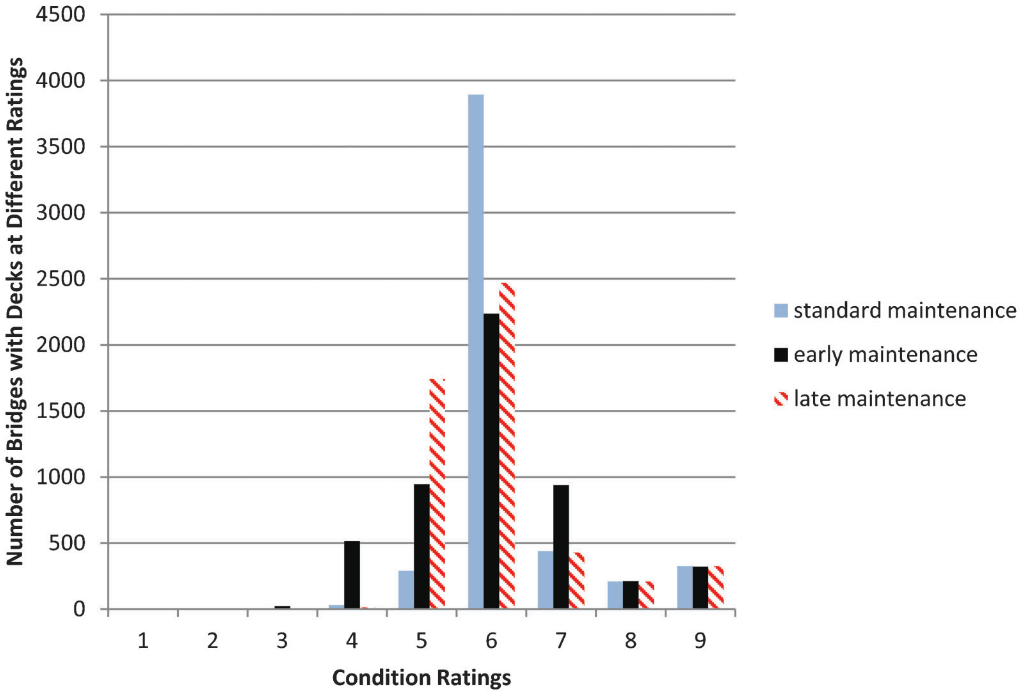


Figure 4.4 Deck condition rating distribution after BMRS run for $250 million budget.

the $150 million budget. This is expected, because treatments are performed on more bridge decks with more funding available.

With a $250 million budget, the standard maintenance strategy has the greatest number of bridge decks with a condition rating above 5. The early maintenance strategy has the greatest number of bridge decks with a condition rating of 6 or greater. This shows that the early maintenance strategy provides a trade-off between quantity and quality. Although the early maintenance strategy has fewer bridge decks with a condition rating above 5 than the standard

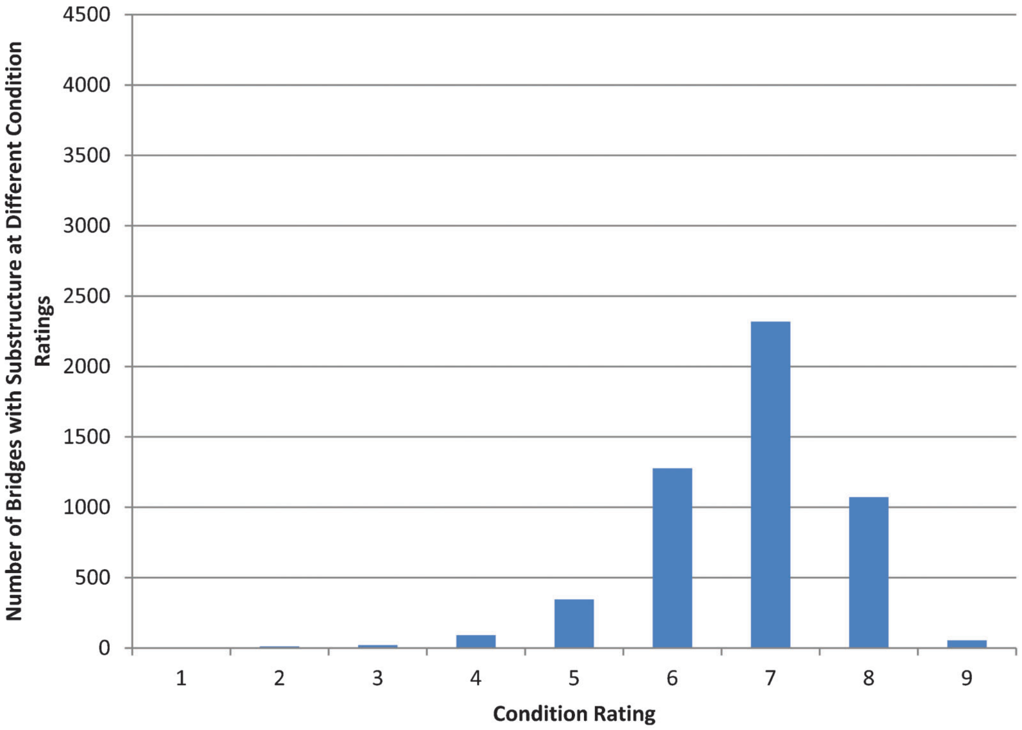


Figure 4.5 Initial substructure condition rating distribution.

maintenance strategy does, it also has more bridge decks with ratings above 6. The late maintenance strategy has the fewest bridge decks with a condition rating below 5, and the greatest number of bridge decks with a condition rating between 4 and 5. The $250 million budget also has fewer bridge decks with condition ratings of 3 or lower and more bridge decks with a condition rating of 5 or greater than the $200 million budget. This is expected, because treatments are performed on more bridge decks with more funding available.

The majority of bridge substructures have a condition rating of 5 or greater. Because 5 is considered fair condition, this means that the majority of bridge substructures are in at least fair condition. Only a few bridge substructures have a condition rating of 3 or lower. Only a few bridge substructures have a condition rating of 3 or lower. A rating of 3 is considered to be poor condition, requiring that maintenance or replacement be performed soon.

Figures 4.6 through 4.8 show the distributions of substructure condition ratings after BMRS performs analysis for each budget level.

With a $150 million budget, the standard maintenance strategy has the greatest number of bridge substructures with a condition rating above 5. The majority of these substructures have a rating between 5 and 6, as shown by the high value in the condition rating bin labeled “6.” The early maintenance strategy and late maintenance strategy give very similar results. The late maintenance strategy has slightly more substructures with ratings between 5 and 7 than the early maintenance strategy does. The early maintenance strategy has more substructures with ratings between 3 and 4.

With a $200 million budget, the standard maintenance strategy has the greatest number of bridge substructures with a condition rating above 5. The majority of these substructures have a rating between 5 and 6, as shown by the high value in the condition rating bin labeled “6.” The early maintenance strategy and late maintenance strategy give very similar results. The late maintenance strategy has slightly more substructures with ratings between 5 and 7 than the early maintenance strategy does. The early maintenance strategy has more substructures with ratings between 3 and 4. The $200 million budget also has fewer bridge substructures with condition ratings of 3 or lower and more bridge substructures with a condition rating of 5 or greater than the $150 million budget. This is expected, because treatments are performed on more bridge substructures with more funding available.

With a $250 million budget, the standard maintenance strategy has the greatest number of bridge substructures with a condition rating above 5. The majority of these substructures have a rating between 5 and 6, as shown by the high value in the condition rating bin labeled “6.” The early maintenance strategy and late maintenance strategy give very similar results. The late maintenance strategy has slightly more substructures with ratings between 5 and 7 than the early maintenance strategy does. The early maintenance strategy has more substructures with ratings between 3 and 4. The late maintenance strategy also has the most substructures with condition ratings between 6 and 7. This is similar to how the early maintenance strategy behaves for bridge decks. The $250 million budget also has fewer bridge substructures with condition ratings of 3 or lower and more bridge substructures with a condition rating of 5 or greater than the $200 million

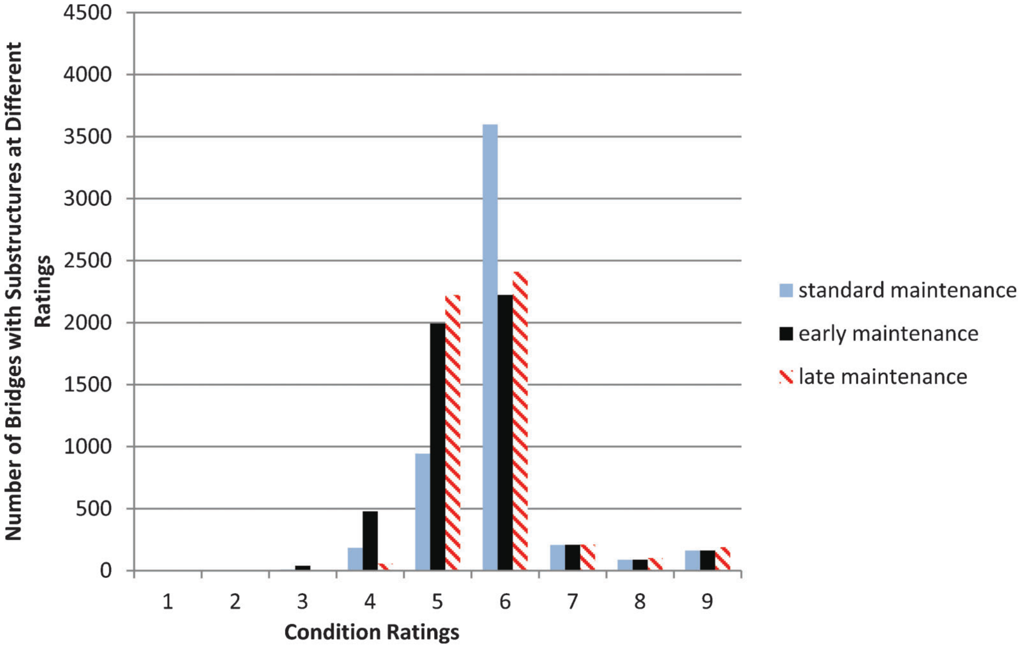


Figure 4.6 Substructure condition rating distribution after BMRS run for $150 million budget.

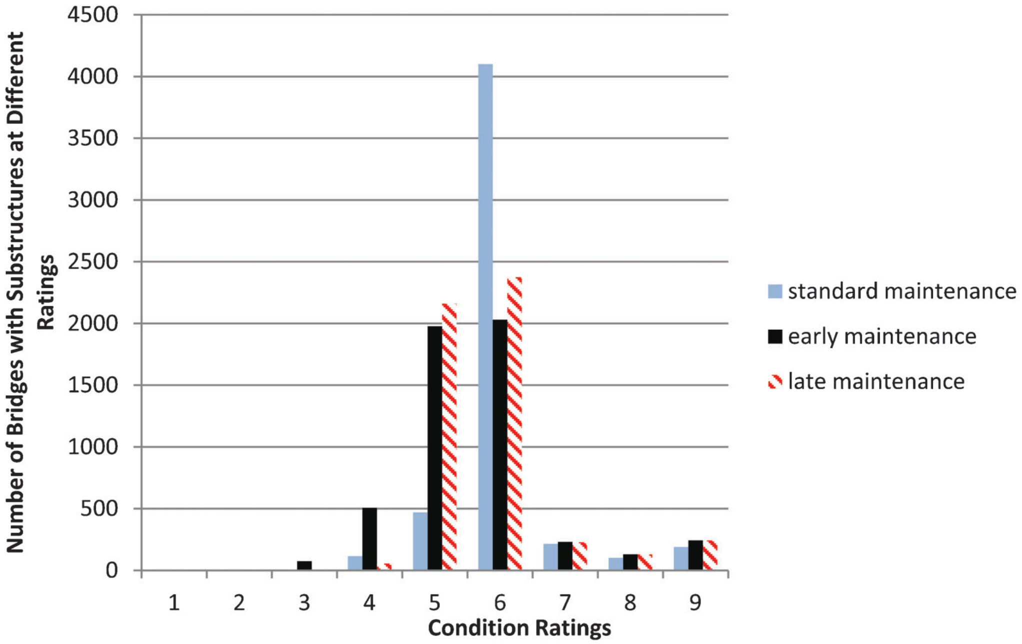


Figure 4.7 Substructure condition rating distribution after BMRS run for $200 million budget.

budget. This is expected, because treatments are performed on more bridge substructures with more funding available.

The majority of bridge superstructures have a condition rating of 5 or greater. Because 5 is considered fair condition, this means that the majority of bridge superstructures are in at least fair condition. Only a few bridge superstructures have a condition rating of 3 or lower. Only a few bridge superstructures have a condition rating of 3 or lower. A rating of 3 is considered to be poor condition, requiring that maintenance or replacement be performed soon.

Figures 4.10 through 4.12 show the distributions of superstructure condition ratings after BMRS performs analysis for each budget level.

With a $150 million budget, the standard maintenance strategy has the greatest number of bridge superstructures with a condition rating above 5. The majority of these superstructures have a rating between 5 and 6, as shown by the high value in the condition rating bin labeled "6." The early maintenance strategy has the greatest number of bridge superstructures with a condition rating of 6 or greater. This shows that the early maintenance strategy provides a trade-off between

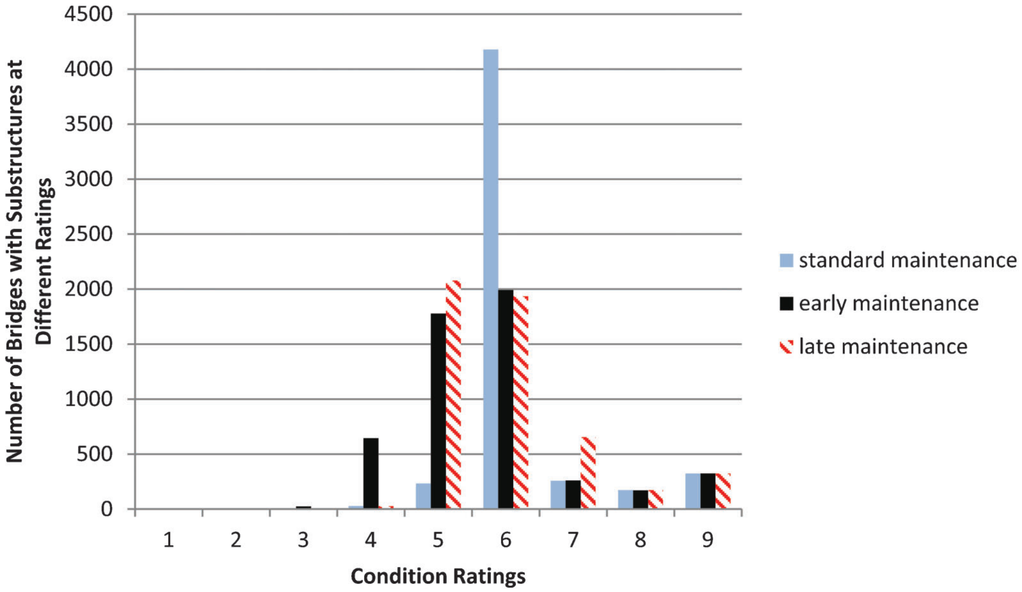


Figure 4.8 Substructure condition rating distribution after BMRS run for $250 million budget.

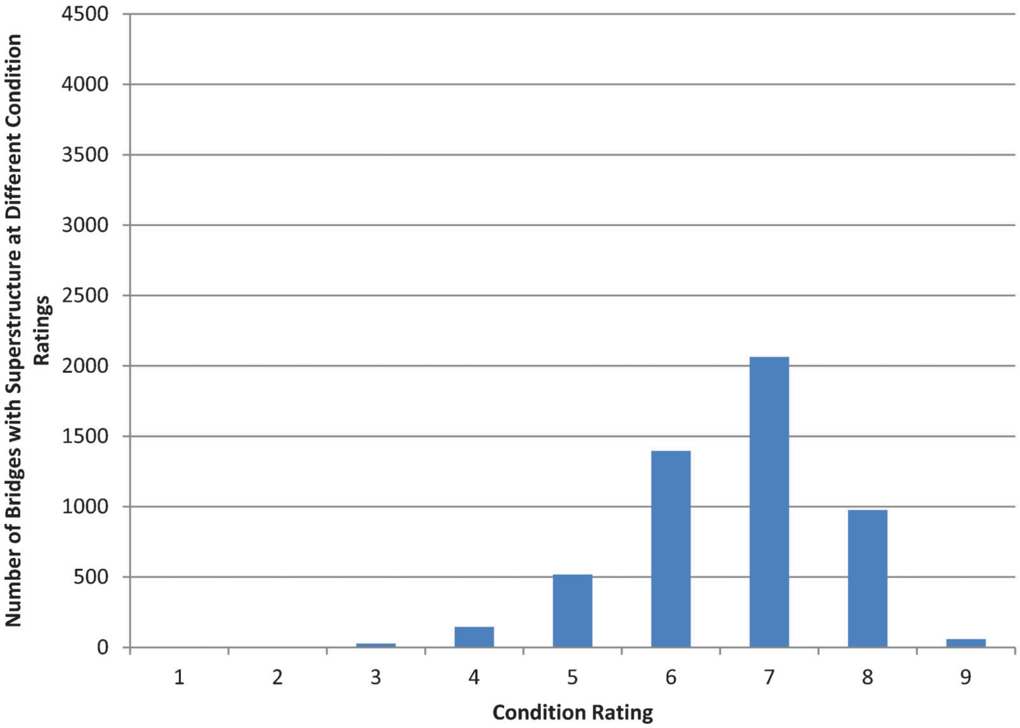


Figure 4.9 Initial superstructure condition rating distribution.

quantity and quality. Although the early maintenance strategy has fewer bridge superstructures with a condition rating above 5 than the standard maintenance strategy does, it also has more bridge superstructures with ratings above 6. These bridge superstructures will take longer to deteriorate to the lower condition ratings, so they will have slightly longer before they must be replaced or have maintenance performed on them. The late maintenance strategy has the greatest number of bridge superstructures with a condition rating between 4 and 5. This shows that the late maintenance strategy has the fewest bridge superstructures in inadequate condition.

With a $200 million budget, the standard maintenance strategy has the greatest number of bridge superstructures with a condition rating above 5. The majority of these superstructures have a rating between 5 and 6, as shown by the high value in the condition rating bin labeled "6." The early maintenance strategy has the greatest number of bridge superstructures with

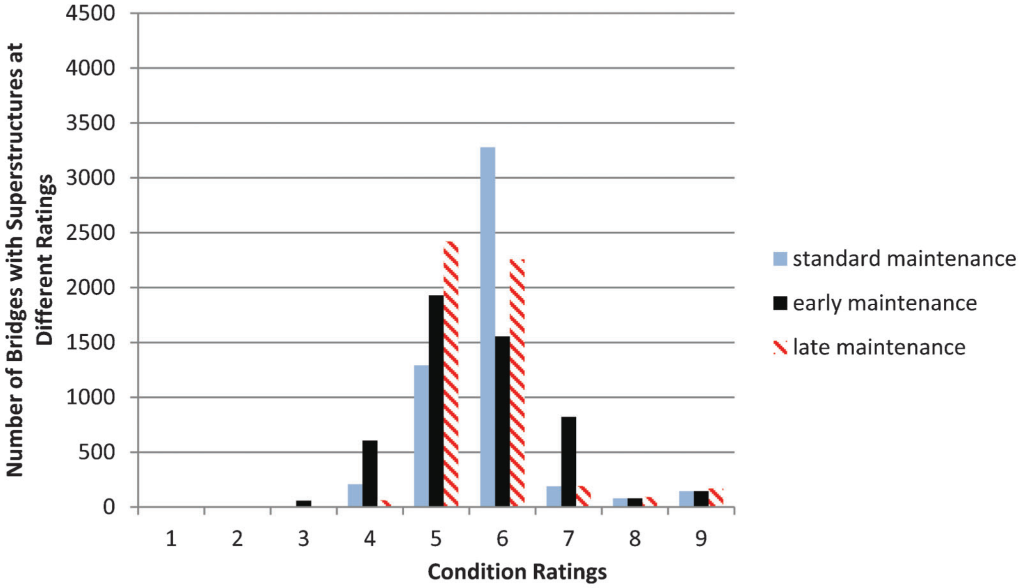


Figure 4.10 Superstructure condition rating distribution after BMRS run for $150 million budget.

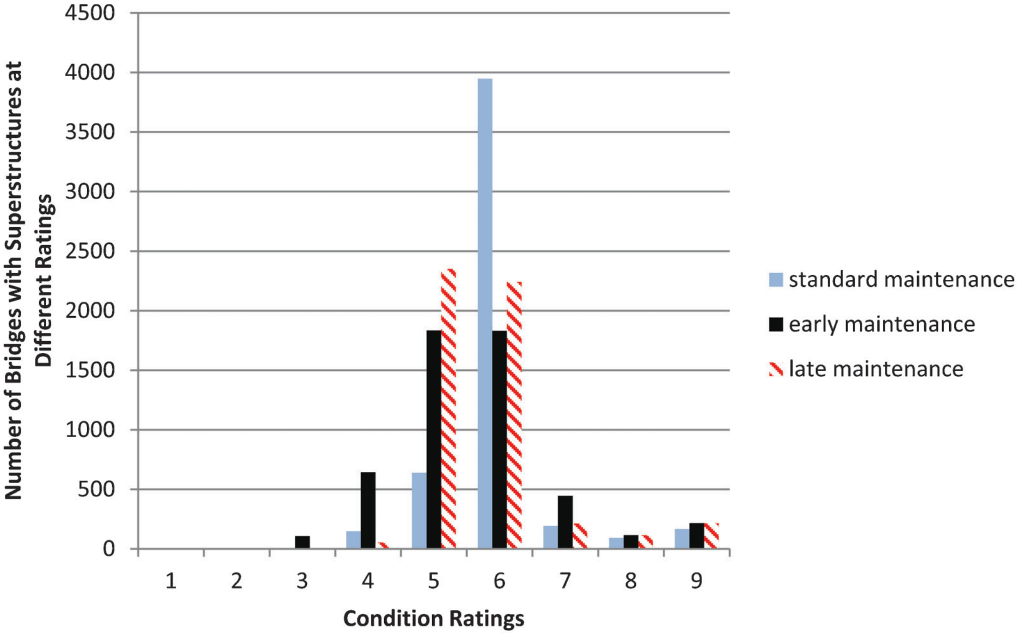


Figure 4.11 Superstructure condition rating distribution after BMRS run for $200 million budget.

a condition rating of 6 or greater. The late maintenance strategy has the greatest number of bridge superstructures with a condition rating between 4 and 5. The $200 million budget also has fewer bridge superstructures with condition ratings of 3 or lower and more bridge superstructures with a condition rating of 5 or greater than the $150 million budget. This is expected, because treatments are performed on more bridge superstructures with more funding available.

With a $250 million budget, the standard maintenance strategy has the greatest number of bridge superstructures with a condition rating above 5. The majority of these superstructures have a rating between 5 and 6, as shown by the high value in the condition rating bin labeled "6." The early maintenance strategy has the greatest number of bridge superstructures with a condition rating of 6 or greater. The late maintenance strategy has the greatest number of bridge superstructures

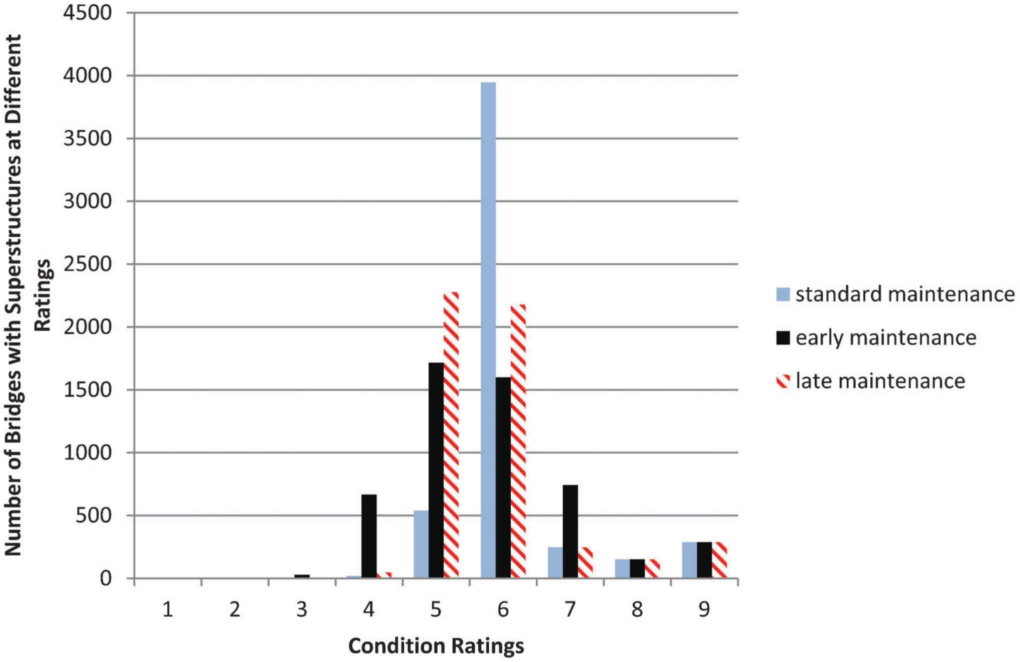


Figure 4.12 Superstructure condition rating distribution after BMRS run for $250 million budget.

with a condition rating between 4 and 5. The $250 million budget also has fewer bridge superstructures with condition ratings of 3 or lower and more bridge superstructures with a condition rating of 5 or greater than the $200 million budget. This is expected, because more treatments are performed on bridge superstructures with more funding available.

4.2. Threshold Analysis

Once the initial and post-run component condition rating analyses were performed, the effectiveness of the different maintenance strategies from the different BMRS runs was evaluated. To evaluate the effectiveness of BMRS runs, a threshold analysis was performed. A threshold analysis allows for comparisons of different budget levels and different sets of trigger values. To perform a threshold analysis, a threshold value must be established. In this project, the threshold value is an NBI component condition rating. For each bridge component, the number of bridges with a component rating greater than or equal to the threshold value was calculated. This number was converted to a percentage of bridges greater than or equal to the threshold value. For each run of the BMRS software, a threshold value of 5 was used. After running the BMRS software, the results for the threshold value analysis were compiled. For each component and budget level, the three different levels of ADT were combined to analyze the whole bridge network. All figures in this section have the y-axis start at a value of 40 instead of a value of 0.

For bridge decks, Figures 4.13 through 4.15 show the results at each budget level.

Figure 4.13 shows that, for a budget of $150 million, both the standard maintenance strategy and early maintenance strategy have almost identical values for the percentage of bridges with deck ratings above the threshold in years 1–10. However, the strategies start to separate in year 11, are very similar in year 20, and then separate again because the early maintenance strategy experiences a drop in the percentage of bridge decks with a condition rating greater than or equal to the threshold of 5. The standard maintenance strategy provides the best results. Until year 30, the early maintenance strategy has a higher percentage of bridge decks greater than or equal to the threshold rating. After year 30, the late maintenance strategy has an equal or higher percentage of bridge decks greater than or equal to the threshold rating. After year 45, the early maintenance strategy again has a higher percentage of bridge decks greater than or equal to the threshold rating.

As the analysis period continues, the bridge deck condition rating distributions tend to have a greater and greater numbers of bridges with condition ratings between 5 and 6. This phenomenon is shown in Figures 4.2 through 4.4, the bridge deck condition rating distribution histograms. When this occurs, all three strategies will tend to display only small fluctuations in percentage of bridges greater than or equal to the threshold rating of 5. This is because bridge decks with a condition rating above 5 will deteriorate below the threshold of 5, and eventually get repaired and jump above the threshold to a value of 6 or 7. Because the rate at which bridge decks deteriorate below the threshold of 5 is very close to the rate at which bridge decks get repaired and jump above the threshold of 5, a

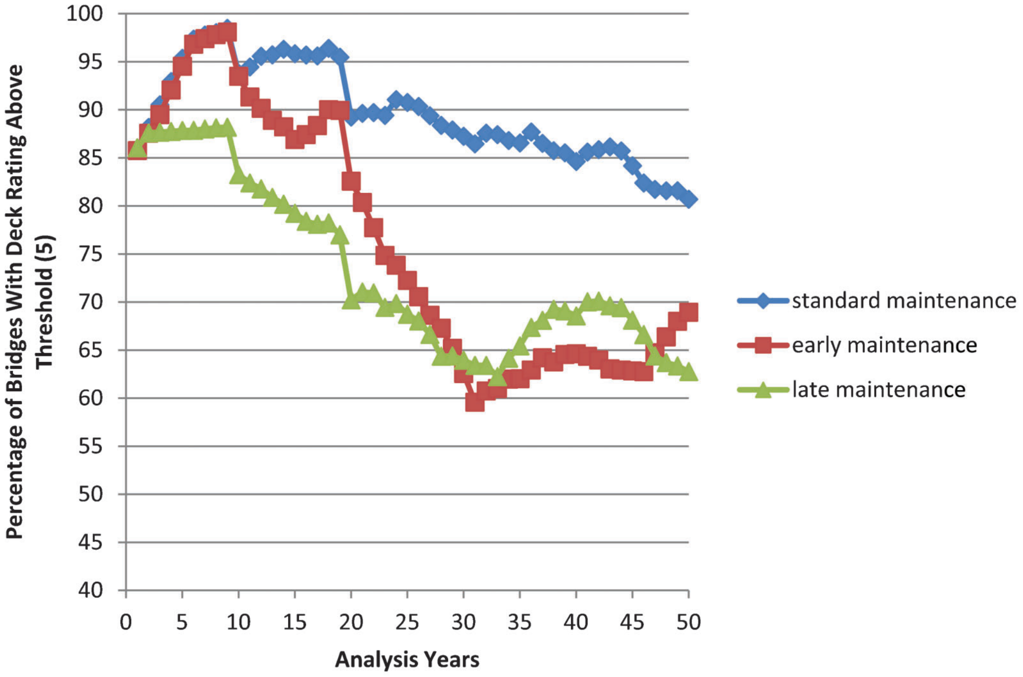


Figure 4.13 Threshold analysis for bridge decks with $150 million budget.

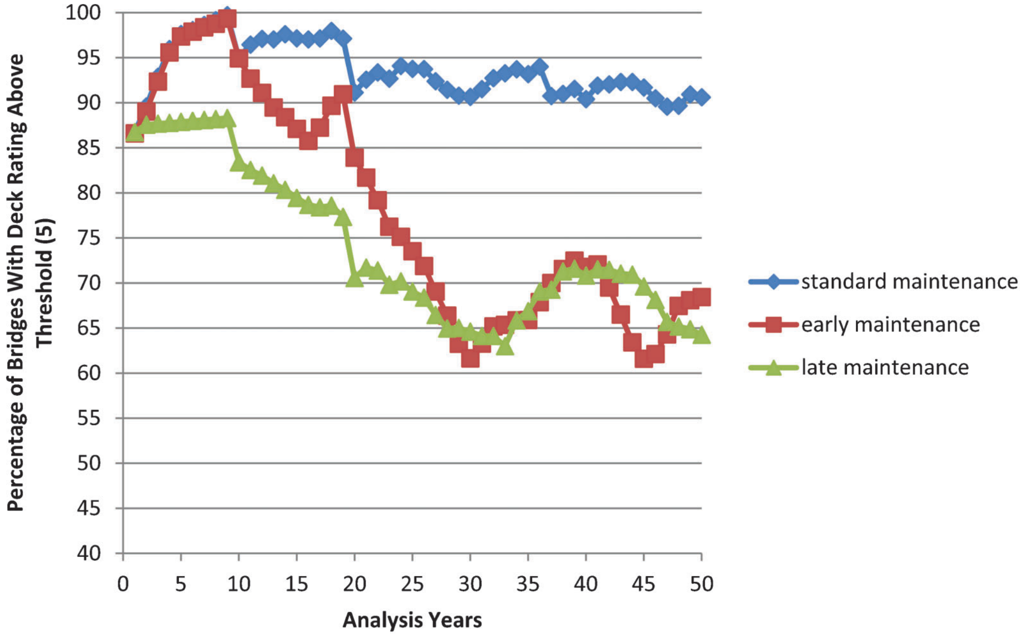


Figure 4.14 Threshold analysis for bridge decks with $200 million budget.

near-equilibrium state is reached for the bridge network. For almost every bridge that deteriorates below the threshold of 5, another bridge will get repaired and jump above the threshold of 5. This near-equilibrium state leads to the small fluctuations in the percentage of bridges greater than or equal to the threshold rating of 5.

The bridges that drop to inadequate condition ratings will have the full bridge replacement applied to them, and have the deck condition rating jump up to 9. Future research should explore combining these strategies. For example, during the first half of the analysis period, the early maintenance strategy can be used; but during the second half of the analysis period, the late maintenance strategy can be used. By updating the BMRS code to allow for changing the maintenance strategy at a certain point in the analysis, this will open up new maintenance strategies to be analyzed.

For every strategy, the highest percentage of bridge decks above the threshold rating for each run occurs in the first 10 years of the analysis period. This can be attributed to the starting values having a high

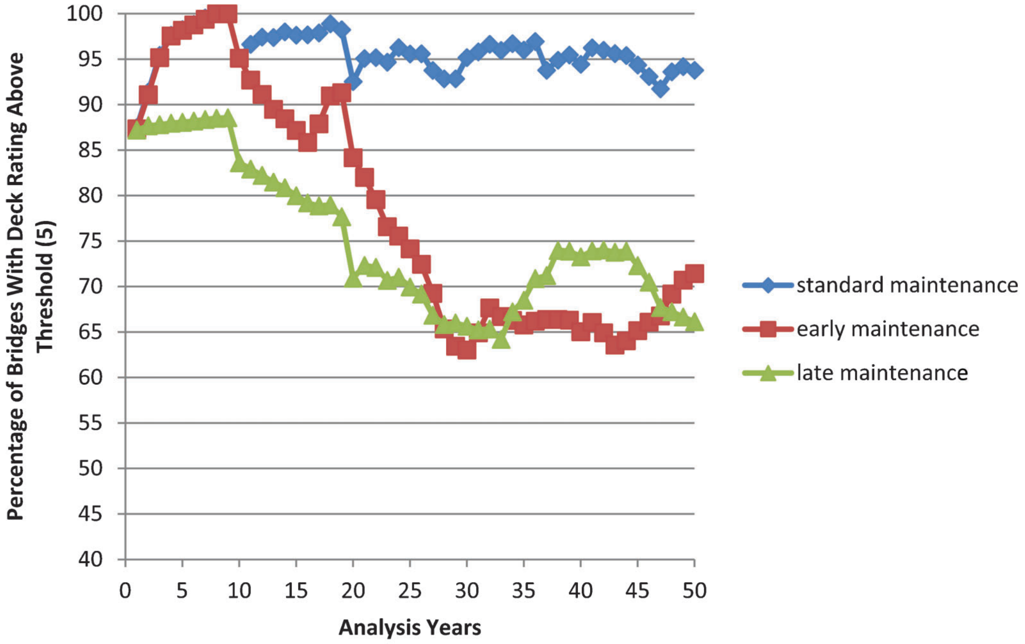


Figure 4.15 Threshold analysis for bridge decks with $250 million budget.

percentage of bridge decks with a condition rating of 5 or greater. In the first 10 years of the analysis period, some of the bridge decks with a condition rating lower than 5 will get treated and will get a performance jump to a condition rating greater than 5. However, the maximum condition rating that a bridge deck can get from a performance jump in BMRS has been set to 7 for this project. The only exception to this is a bridge replacement, which can reset the condition rating to a value of 9. As the analysis period continues, decks with a condition rating of 8 or 9 will eventually deteriorate below a rating of 7. Because these decks will only go above a rating of 7 with a bridge replacement, the rate at which bridge decks will drop below a condition rating of 5 increases, because the bridges will take less time to drop below a condition rating of 5. As bridges continue to deteriorate after the first 10 years of the analysis, the rate at which bridges will drop lower than a condition rating of 5 surpasses the rate at which bridge deck repairs will move condition ratings greater than or equal to a condition rating of 5. This difference in rates will lead to a lower percentage of bridge decks having a condition rating greater than or equal to the threshold rating of 5. If more funding would be available, then the rate at which bridge decks would become greater than or equal to the threshold rating of 5 would increase, and a higher percentage of bridge decks would be greater than or equal to the threshold value of 5. Future research on this subject should check the assumption in BMRS that bridge ratings can only have a performance jump to a set value, such as 7. Eventually, these rates will balance out, because the worst bridges are replaced and the phenomenon where most of the bridges have condition ratings between 5 and 6 will occur.

With a $200 million budget; the behavior of the bridge deck runs is very similar to that of a $150 million budget. The major difference is that, with a higher budget, more bridges can be repaired. This means that, although the shapes of the curves for each deck run are similar, for each curve, the number of bridge decks greater than or equal to the threshold rating is slightly higher. Table 4.1 gives the number of bridge decks greater than or equal to the threshold rating for each strategy after year 50 of each run.

With a $250 million budget; the behavior of the bridge deck runs is very similar to that of a $150 million and $200 million budget. The major difference is that with a higher budget, more bridges can be repaired. This means that, although the shapes of the curves for each deck run are similar, for each curve, the number of bridge decks with a component condition rating greater than or equal to the threshold rating is slightly higher for the $250 million budget. Table 4.1 gives the percentage of bridge decks greater than or equal to the threshold rating for each strategy after year 50 of each run.

For bridge substructures; Figures 4.16 through 4.18 show the results for each budget level.

Figure 4.16 shows that, with a budget of $150 million, both the standard maintenance strategy and early maintenance strategy have almost identical values for the percentage of bridges with substructure ratings above the threshold in years 1–10. However, the strategies start to separate in year 11, are very similar in year 15, and then separate again because the early maintenance strategy experiences a drop in the percentage of bridge substructures with a condition rating greater than or equal to the threshold of 5. Until year 30, the early maintenance strategy has a higher percentage of bridge substructures greater than or equal to the threshold rating. After year 30, the late maintenance strategy has an equal or higher percentage of bridge substructures with component condition ratings greater than or equal to the threshold rating. After year 45, the early maintenance strategy again has a higher percentage of bridge substructures greater than or equal to the threshold rating.

Overall, the highest percentage of bridge substructures with component condition ratings greater than or equal to the threshold rating for each run occurs in the first 10 years of the analysis period. This behavior is similar to the bridge deck runs; which can be attributed to the starting values having a high percentage of bridge decks with a condition rating greater than or equal to 5. The reasoning for this behavior is the same as for the bridge deck runs.

Once again, the standard maintenance strategy performs the best of all three strategies. The difference in the substructure strategies is similar to the difference in the deck strategies. The reasoning that the standard maintenance strategy performs the best is again similar to the reasoning for why the standard maintenance strategy performs the best for bridge decks.

With a $200 million budget; the behavior of the bridge substructure runs is very similar to that of a $150 million budget. The major difference is that with a higher budget, more bridges can be repaired. This means that although the shapes of the curves for each substructure run are similar, for each curve, the number of bridge substructures with component condition ratings greater than or equal to the threshold rating is slightly higher. Table 4.2 gives the percentage of bridge

TABLE 4.1
Percentage of bridge decks greater than or equal to threshold rating (5) for each strategy

Budget	Standard maintenance	Early maintenance	Late maintenance
$150 million budget	80.7	68.9	62.8
$200 million budget	90.6	68.4	64.3
$250 million budget	93.8	71.4	66.1

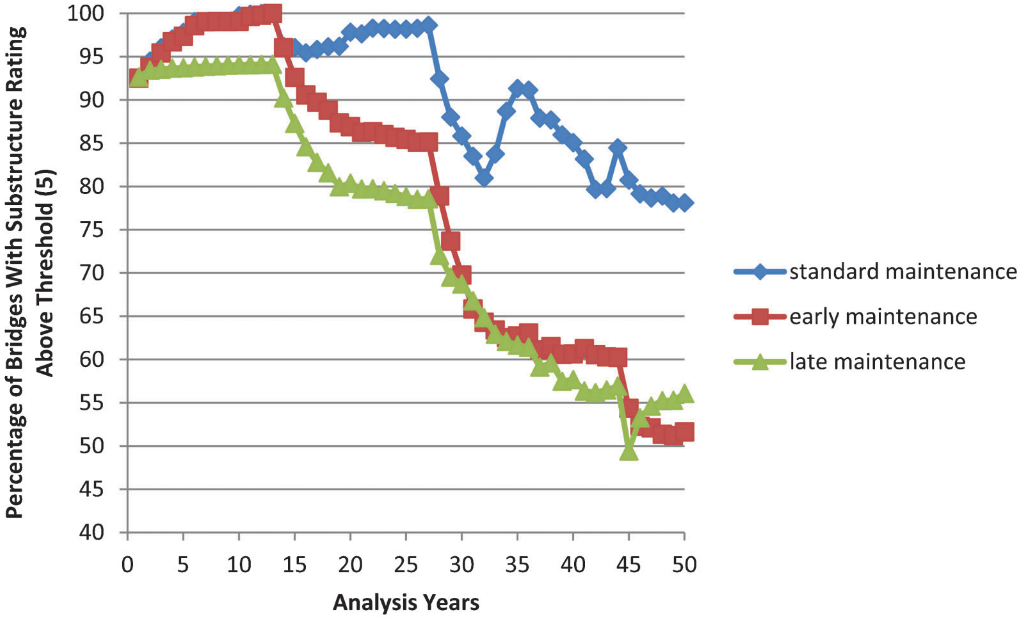


Figure 4.16 Threshold analysis for bridge substructures with $150 million budget.

substructures greater than or equal to the threshold rating for each strategy after year 50 of each run.

With a $250 million budget; the behavior of the bridge substructure runs is very similar to that of a $150 million and $200 million budget. The major difference is that with a higher budget, more bridges can be repaired. This means that although the shapes of the curves for each substructure run are similar, for each curve, the number of bridge substructures with component condition ratings greater than or equal to the threshold rating is slightly higher. Table 4.2 gives the percentage of bridge substructures greater than or equal to the threshold rating for each strategy after year 50 of each run.

For bridge superstructures; Figures 4.19 through 4.21 show the results for each budget level.

Figure 4.19 shows that, with a budget of $150 million, the standard maintenance strategy and early maintenance strategy have almost identical values for the percentage of bridges with substructure ratings

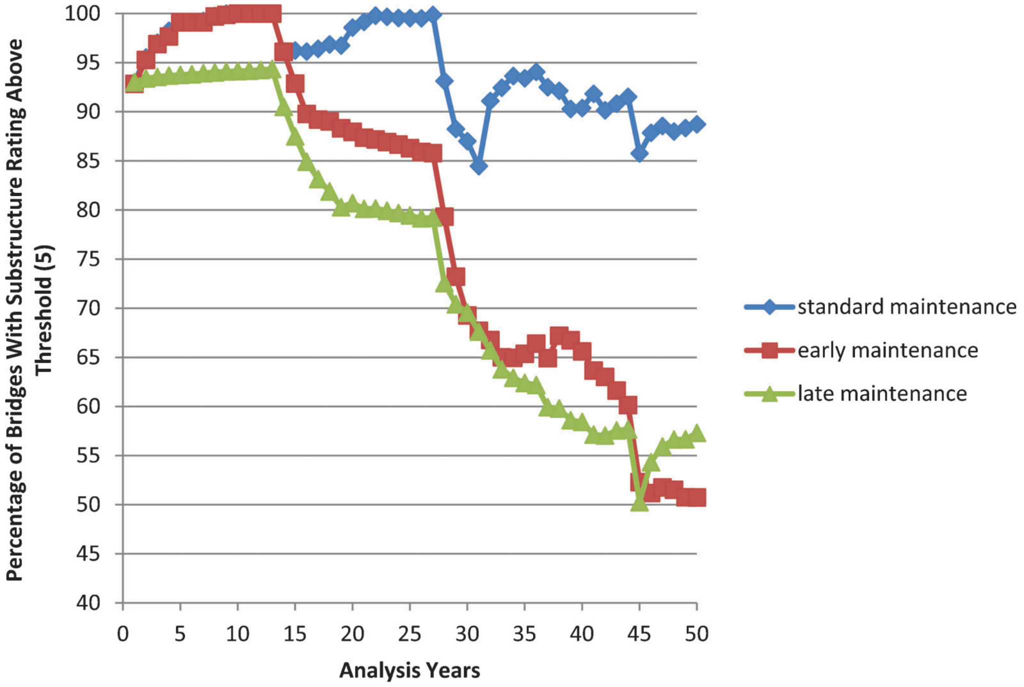


Figure 4.17 Threshold analysis for bridge substructure with $200 million budget.

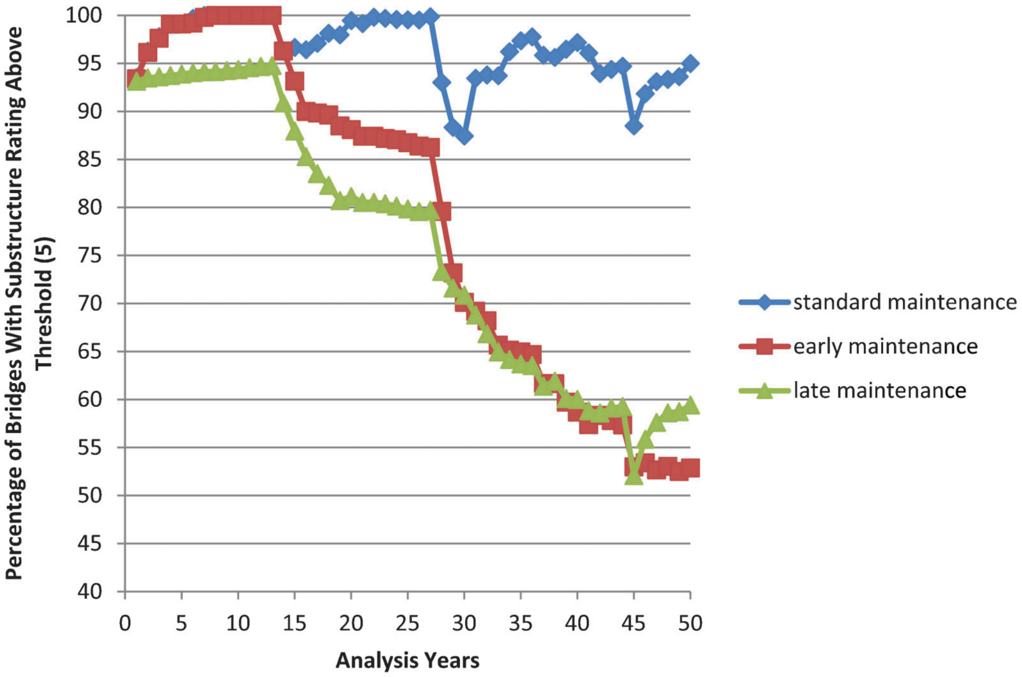


Figure 4.18 Threshold analysis for bridge substructure with $250 million budget.

TABLE 4.2
Percentage of bridge substructures greater than or equal to threshold rating (5) for each strategy

Budget	Standard maintenance	Early maintenance	Late maintenance
$150 million budget	78.1	51.6	56.1
$200 million budget	88.7	50.7	57.3
$250 million budget	95.0	52.9	59.4

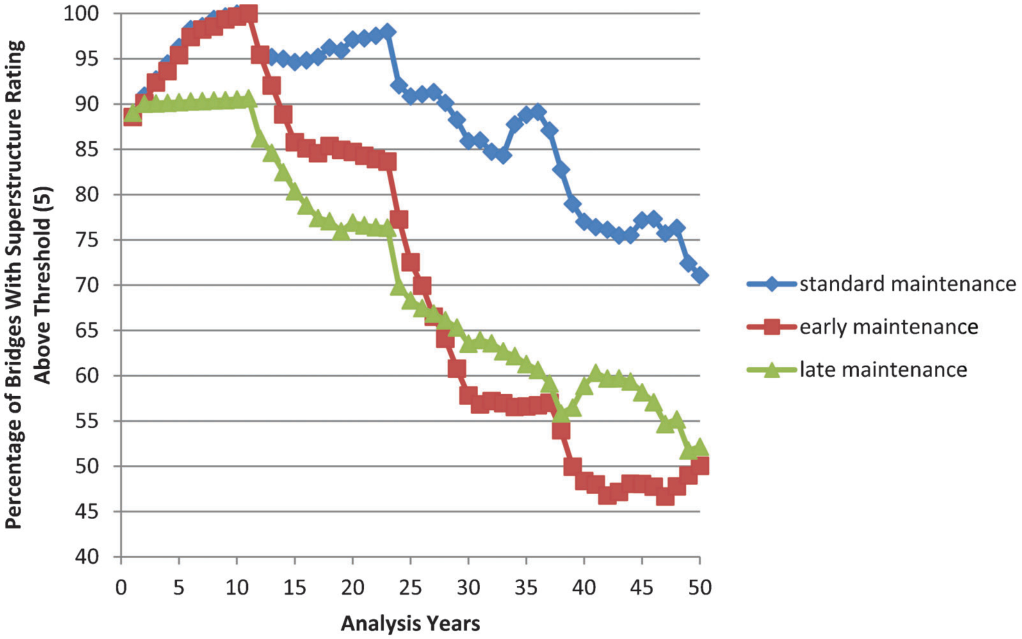


Figure 4.19 Threshold analysis for bridge superstructures with $150 million budget.

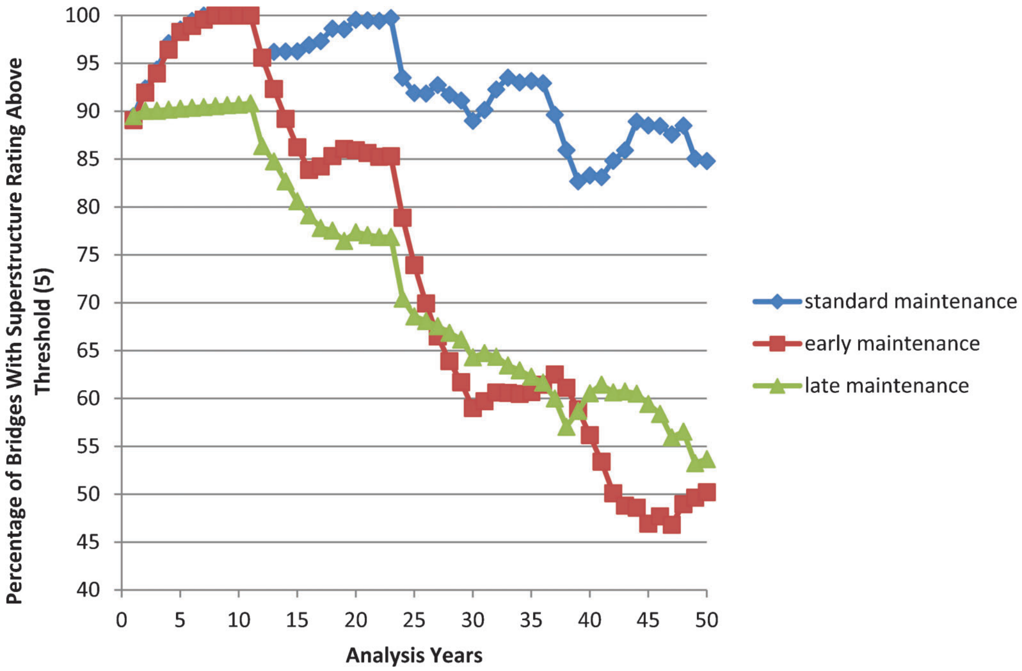


Figure 4.20 Threshold analysis for bridge superstructure with $200 million budget.

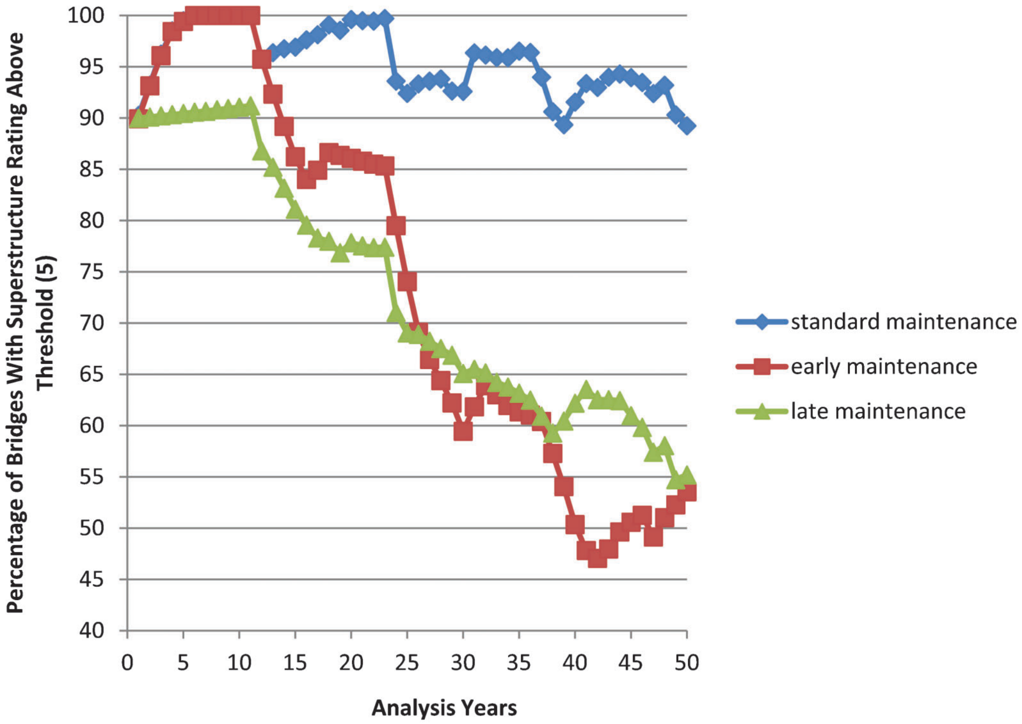


Figure 4.21 Threshold analysis for bridge superstructure with $250 million budget.

greater than or equal to the threshold in years 1–10. However, the strategies start to separate in year 11 because the early maintenance strategy experiences a drop in the percentage of bridge substructures with a condition rating greater than or equal to the threshold of 5. Until year 25, the early maintenance strategy has a higher percentage of bridge substructures greater than or equal to the threshold rating. After year 25, the late maintenance strategy has an equal or higher percentage of bridge substructures greater than or equal to the threshold rating.

Overall, the highest percentage of bridge superstructures with condition ratings greater than or equal to the threshold rating for each run occurs in the first 10 years of the analysis period. This behavior is similar to the bridge deck and substructure runs; which can be attributed to the starting values having a high percentage of bridge decks with a condition rating of 5 or higher. The reasoning for this is the same as for the bridge deck and substructure runs.

Once again, the standard maintenance strategy performs the best of all three strategies. The difference in the superstructure strategies is similar to the difference in the deck strategies. The reasoning that the standard maintenance strategy performs the best is again similar to the reasoning for why the standard maintenance strategy performs the best for bridge decks and substructures.

With a $200 million budget; the behavior of the bridge superstructure runs is very similar to that of a $150 million budget. The major difference is that with a higher budget, more bridges can be repaired. This means that although the shapes of the curves for each superstructure run are similar, for each curve, the number of bridge superstructure with component condition ratings greater than or equal to the threshold rating is slightly higher. Table 4.3 gives the percentage of bridge superstructures greater than or equal to the threshold rating for each strategy after year 50 of each run.

With a $250 million budget; the behavior of the bridge superstructure runs is very similar to that of a $150 million and $200 million budget. The major difference is that with a higher budget, more bridges can be repaired. This means that although the shapes of the curves for each superstructure run are similar, for each curve, the number of bridge superstructure with component condition ratings greater than or equal to the threshold rating is slightly higher. Table 4.3 gives the percentage of bridge superstructures greater than or equal to the threshold rating for each strategy after year 50 of each run.

4.3. Evaluating Results of Distribution Analysis and Threshold Analysis

The distribution analysis shows that the standard maintenance strategy, the early maintenance strategy, and late maintenance strategy all perform well in different ways. Figures 4.2 to 4.4, Figures 4.6 to 4.8, and Figures 4.10 to 4.12 show that the standard maintenance strategy has the highest number of bridge components above a rating of 5 by the end of the 50-year analysis period. These figures also show that the early maintenance strategy has the highest number of bridge components with a condition rating of 6 or better by the end of the analysis period. These figures also show that the late maintenance strategy has the lowest number of bridge components with a condition rating worse than 3 by the end of the analysis period. All three of the following performance measures are desirable: highest number of bridge components with a rating of better than 5, highest number of bridge components with a condition rating of 6 or better, and lowest number of bridge components with a condition rating worse than 3. Because each bridge management strategy performs the best in only one performance measure, further analysis is needed beyond the distribution analysis.

The threshold analysis provides some additional insight into how well each bridge management strategy performs. The threshold analysis clearly shows that the standard maintenance strategy performs the best. For every figure, Figure 4.13 to Figure 4.21, the standard maintenance strategy has the highest percentage of bridge components above the performance threshold of 5 by year 15, or even earlier in the analysis period for some components. After the standard maintenance strategy gets to the highest percentage of bridge components above the performance threshold, no other strategy has a higher percentage of bridge components above the performance threshold for any remaining year of the analysis period. This shows that the standard maintenance strategy consistently performs the best in the threshold analysis for every bridge component at every budget level.

The distribution analysis and threshold analysis each evaluate how well a bridge management strategy is performing. Each method of analysis—distribution analysis and threshold analysis—only gives a partial

TABLE 4.3
Percentage of bridge superstructures greater than or equal to threshold rating (5) for each strategy

Budget	Standard maintenance	Early maintenance	Late maintenance
$150 million budget	71.1	50.1	52.2
$200 million budget	84.8	50.2	53.7
$250 million budget	89.3	53.6	55.2

evaluation of each bridge management strategy. These two methods of analysis need to be combined in some way to fully evaluate a bridge management strategy. To meet this need to evaluate bridge management strategies, an index function was created, and index analysis was performed for each bridge management strategy. More details about the index function and the resulting analysis are available in Section 3 of Chapter 5.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Implications of Different Bridge Management Strategies

This project investigated varying two different elements of bridge management strategies. The first element was trigger value at which different treatments were performed. The second element was the budget.

To test variations in the trigger values, three different bridge management strategies were proposed: a standard maintenance strategy, an early maintenance strategy, and a late maintenance strategy. Each strategy has six different treatments that can be applied to different bridge components. Each treatment has a range of trigger values at which the treatment can be performed. The ranges of trigger values for these treatments were based on a dTIMS run performed by INDOT for this project. The details of the different trigger values for these strategies are discussed in Section 4 of Chapter 3.

For each bridge management strategy, five different maintenance treatments and one replacement treatment were used. These treatments were selected from a dTIMS run performed by INDOT for this project. When bridge components deteriorate to a component condition rating of 6 or below, maintenance treatments can be performed on the components to increase their condition ratings. The rate at which this deterioration occurs is taken from deterioration curves developed for IBMS (Sinha et al., 2009). Each maintenance treatment changed either the bridge deck condition rating, the substructure condition rating, or the superstructure condition rating. For example a deck rehabilitation treatment will increase the deck condition rating from its current rating to a rating of 6. (“Performance jumps” in BMRS always increase the component condition rating to a set value regardless of the starting condition rating.) The bridge components with the very worst component condition ratings are considered candidates for bridge replacement treatment. The bridges that are candidates for a bridge replacement are found by using the sorting process discussed in Section 3 of Chapter 3. There is an important difference between replacement treatments and maintenance treatments. Instead of just increasing one component condition rating, a bridge replacement treatment increased all three of the condition ratings. For example, a bridge replacement treatment will increase the deck condition rating from its current rating to a rating of 9, the substructure condition rating from its current rating to a rating of 9, and the superstructure condition rating from its current rating to a rating of 9. Figure 5.1 illustrates the difference in performance jumps between a maintenance treatment and replacement treatment using a maintenance treatment for a bridge deck and a replacement treatment for the whole bridge.

To test variations in the budget, three different annual budget levels were used: $150 million, $200 million, and $250 million. The $150 million amount represents the approximate current level of spending for bridge maintenance and replacement by INDOT. The $200 million budget and $250 million budget represent increases in the budget for Indiana. Each time a treatment is performed on a bridge component in BMRS, the cost of the treatment is removed from the budget until the budget is used up. The costs for each treatment do not vary from strategy to strategy and were taken from a dTIMS run performed by INDOT for this project.

In the dTIMS run performed by INDOT for this project, bridge replacement annually used an average of 20.31% of the total budget. Because a bridge replacement treatment affects bridge component condition ratings differently than a bridge maintenance treatment, the three different budget levels were each spilt up into a maintenance and replacement component. The maintenance and replacement components of the budget were then divided into three different categories based on the ADT of traffic approaching a bridge. The procedure for splitting the budget is discussed in Section 4 of Chapter 3.

One element of bridge management that was not changed in this project was the number of bridge replacements performed. For all strategies, a constant percentage of 20.31% of the budget was dedicated to bridge replacement. Future research should look at the effects of dedicating different percentages of the budget to replacement treatments versus the percentage of budget dedicated to maintenance treatments.

When using BMRS to test different bridge management strategies, there are a few important modeling simplifications and assumptions that should be taken into consideration when analyzing BMRS results. One simplification is the number of treatments in a BMRS bridge management strategy. Each bridge management strategy only uses 6 different treatments, while IBMS and dTIMS have 55 different treatments. BMRS also does not account for economies of scale in costs of treatments; the costs are based on an average value for all bridges and were taken from the dTIMS run performed by INDOT for this project. BMRS also assumes that a performance jump will improve a component condition rating to a set value, regardless of the starting condition of that component. For example, for a bridge deck that has a deck rehabilitation treatment performed on it, the deck condition rating will be 6 after the treatment is performed, regardless of whether the deck condition rating before the treatment was 3, 4, or 5. BMRS assumes improvements from a treatment will occur in the year after the treatment was performed.

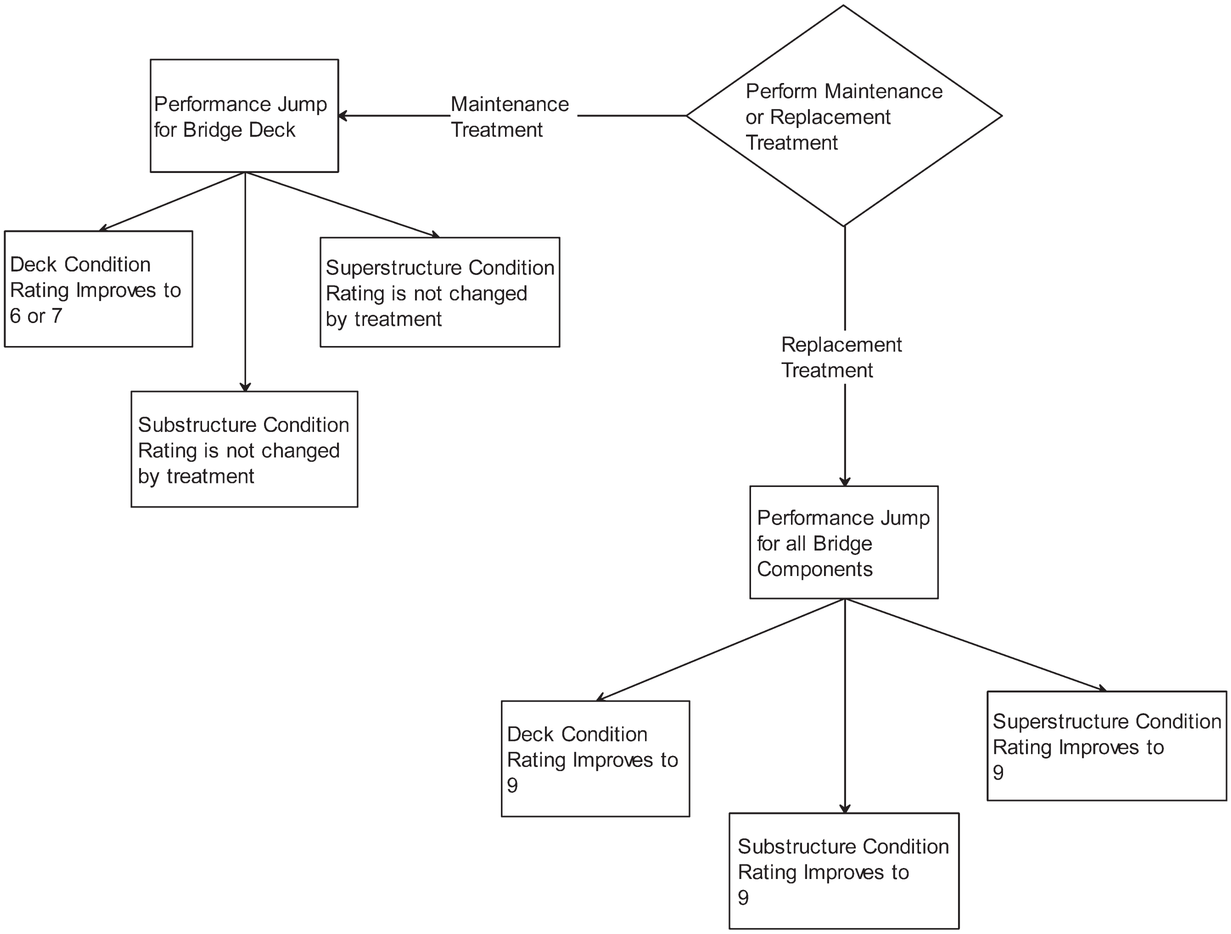


Figure 5.1 Performance jumps for maintenance and replacement treatments.

The strategy that performed the best was the standard maintenance strategy. This strategy performed the best for all three budget levels tested. Section 3 of this chapter gives more detailed results for the performance of the standard maintenance strategy, as well as the other two strategies.

5.2. Effects of Varying Budget

Figure 5.2 and Table 5.1 show the percentages of bridge component condition ratings greater than or equal to the performance threshold of 5 for the standard maintenance strategy at the three different budget levels. In most figures in this report, when percentages of component condition ratings greater than or equal to the performance threshold are displayed, they are for only one bridge component at a time. In the figures and tables in this section, the percentages displayed are for all three bridge components combined. All figures in this section have the y-axis start at a value of 40 instead of a value of 0.

As Table 5.1 shows, for the standard maintenance strategy, the differences in the percentage of bridge component condition ratings greater than or equal to the performance threshold changes dramatically after year 25. This can be seen using a percentage difference analysis, which is performed using Equation 5.1.

$$\text{Percentage Difference} = \frac{P_{above\ threshold\ 2} - P_{above\ threshold\ 1}}{(P_{above\ threshold\ 2} + P_{above\ threshold\ 1}) * 0.5} * 100 \tag{5.1}$$

The following is an example of using Equation 5.1 for year 25 of the standard maintenance strategy:

(1) $P_{\text{above threshold 2}} = 95.84$ (value for \$250 million budget) and $P_{\text{above threshold}} = 93.27$ (value for \$150 million budget)

(2) $$\textit{Difference in threshold} = \frac{95.84 - 93.27}{(95.84 + 93.27) * 0.5} * 100 = 2.72\%$$

In year 25, the \$250 million budget has 2.72% more bridge components greater than or equal to the threshold than the \$150 million budget and the \$200 million budget has 1.91% more bridge components greater than or equal to the threshold than the \$150 million budget. By year 50, the \$250 million budget has 18.94% more bridge components greater than or equal to the threshold than the \$150 million budget and the \$200 million budget has 13.86% more bridge components greater than or equal to the threshold than the

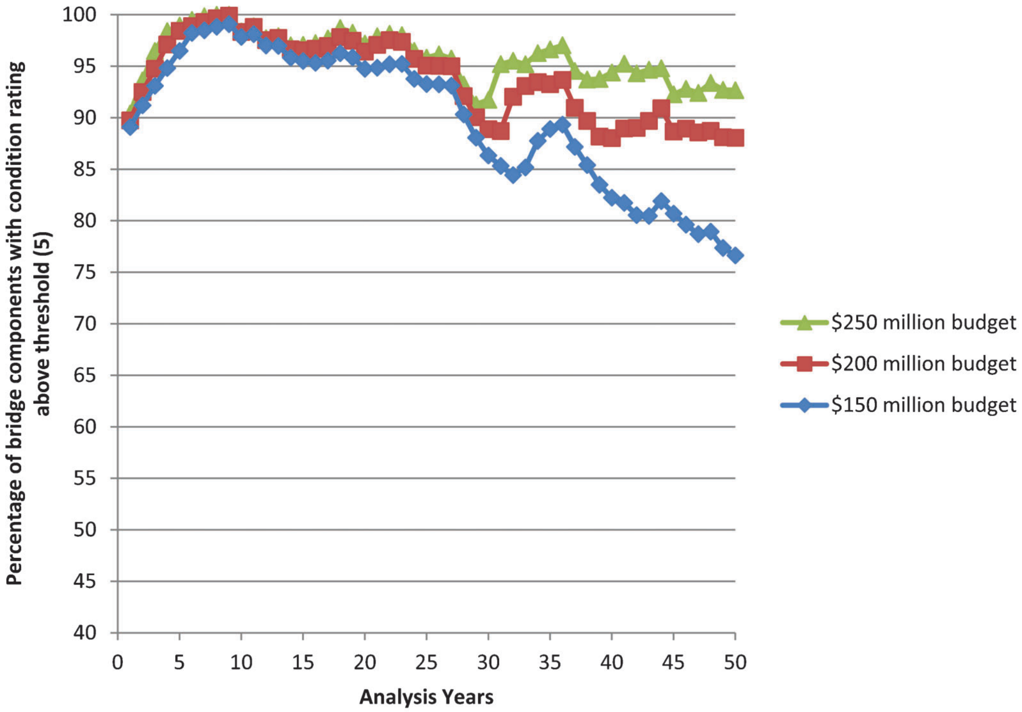


Figure 5.2 Comparison of budget levels for standard maintenance strategy threshold analysis.

$150 million budget. This shows that as the analysis period continues, the benefits of a greater budget become more apparent.

Figure 5.3 and Table 5.2 show the percentages of bridge component condition ratings greater than or equal to the performance threshold of 5 for the early maintenance strategy.

As Table 5.2 shows, for the early maintenance strategy, the differences in the percentage of bridge component condition ratings greater than or equal to the performance threshold changes much less dramatically after year 25 than the standard maintenance strategy does. This can be seen using a percentage difference analysis. In year 25, the $250 million budget has 2.02% more bridge components greater than or equal to the threshold than the $150 million budget. By year 50, the $250 million budget has 4.13% more bridge components greater than or equal to the threshold than the $150 million budget. Also, the overall percentage of bridge components greater than or equal to the threshold of 5 is much lower in year 50 for the early maintenance run. For the standard maintenance strategy the percentage of bridge components greater than or equal to the threshold of 5 in year 50 is 92.67% for a budget of $250 million. For the early maintenance strategy, this percentage is only 59.29%. When analyzing these results, it is important to also remember the condition rating distribution histograms in Chapter 4. Although the percentage of bridge components greater than or equal to the threshold is lower for the early maintenance run, there are also more bridges with condition ratings greater than or equal to 6.

TABLE 5.1
Comparison of budget levels for standard maintenance strategy threshold analysis (5 year increments)

Year	$150 million budget	$200 million budget	$250 million budget
5	96.5	98.4	98.9
10	97.8	98.3	98.4
15	95.5	96.6	97.1
20	94.7	96.4	97.2
25	93.3	95.1	95.8
30	86.3	88.9	91.7
35	88.9	93.3	96.6
40	82.2	88.0	94.4
45	80.7	88.7	92.3
50	76.6	88.0	92.7

Figure 5.4 and Table 5.3 show the percentages of bridge component condition ratings greater than or equal to the performance threshold of 5 for the late maintenance strategy.

As Table 5.3 shows, for the late maintenance strategy, the differences in the percentage of bridge components greater than or equal to the performance threshold changes much less dramatically after year 25 than the standard maintenance strategy does. This can be seen using a percentage difference analysis. In year 25, the $250 million budget has 1.35% more bridge components greater than or equal to the threshold than the $150 million budget. By year 50, the $250 million budget has 5.54% more bridge components greater than

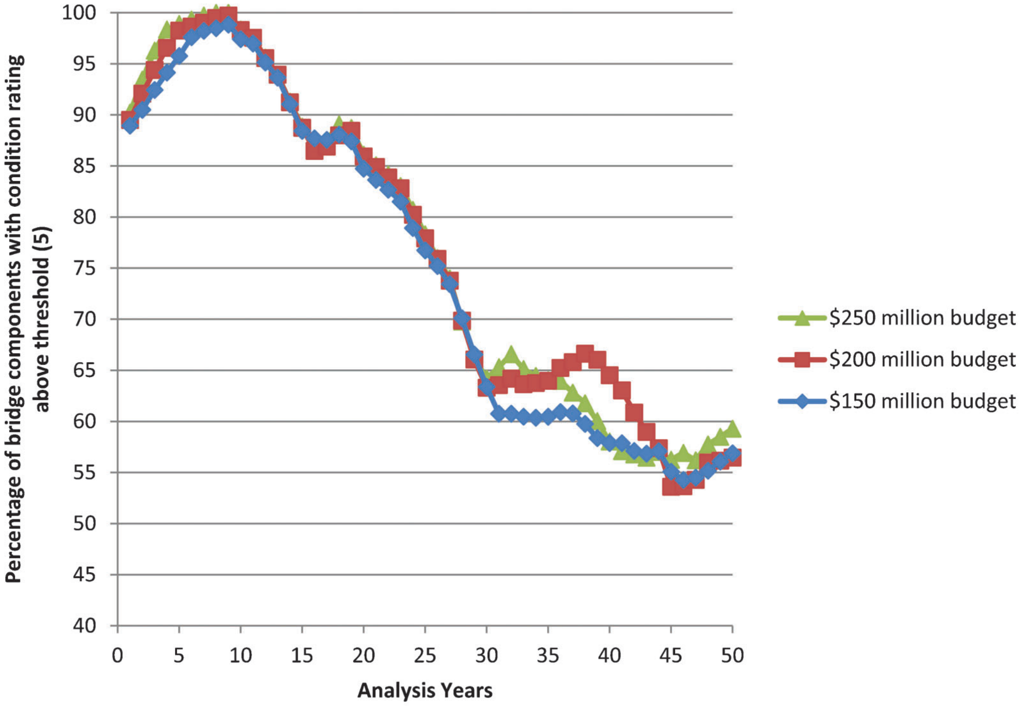


Figure 5.3 Comparison of budget levels for early maintenance strategy threshold analysis.

or equal to the threshold than the $150 million budget. Also, the overall percentage of bridge components greater than or equal to the threshold of 5 is much lower in year 50 for the early maintenance run. For the standard maintenance strategy the percentage of bridge components greater than or equal to the threshold of 5 in year 50 is 92.67% for a budget of $250 million. For the late maintenance strategy, this percentage is only 60.25%. When analyzing these results, it is important to also remember the condition rating distribution histograms in Chapter 4. Although the percentage of bridge components greater than or equal to the threshold is lower for the late maintenance run, there are also fewer bridges with condition ratings less than or equal to 3.

TABLE 5.2
Comparison of budget levels for early maintenance strategy threshold analysis (5 year increments)

Year	$150 million budget	$200 million budget	$250 million budget
5	95.8	98.3	98.9
10	97.4	98.3	98.4
15	88.4	88.7	88.9
20	84.7	85.9	86.1
25	76.7	77.9	78.3
30	63.4	63.3	64.2
35	60.5	64.0	64.0
40	57.9	64.5	58.0
45	55.1	53.6	56.2
50	56.9	56.5	59.3

5.3. Recommendations

After looking at the differences in the performance of the three different strategies, it is important to choose the strategy that displays the best performance. Because of the constraints of the BMRS program, it is not recommended that one of the treatment strategies be implemented exactly as programmed into BMRS. Rather, it is recommended that the concepts behind the strategy that is chosen be implemented instead of the exact strategy.

To compare the three different strategies, there are three different elements that should be considered. The first element that should be considered is the percentage of bridge components greater than or equal to the performance threshold. This represents the bridge components that are considered to be in adequate condition. Bridge components below this threshold condition rating will need to have maintenance or replacement performed on them soon. The second element that should be considered is the percentage of bridge component condition ratings greater than or equal to 6. This represents the bridge components with only minor deterioration. These bridge components will take longer than bridges with condition ratings less than 6 to deteriorate to a condition rating where maintenance or replacement must be performed. The third element is the percentage of bridge component condition ratings less than or equal to 3. This represents the bridge components in inadequate condition. Bridge components in inadequate condition require maintenance or replacement to be performed on them. If maintenance or replacement is not performed on these bridges, users

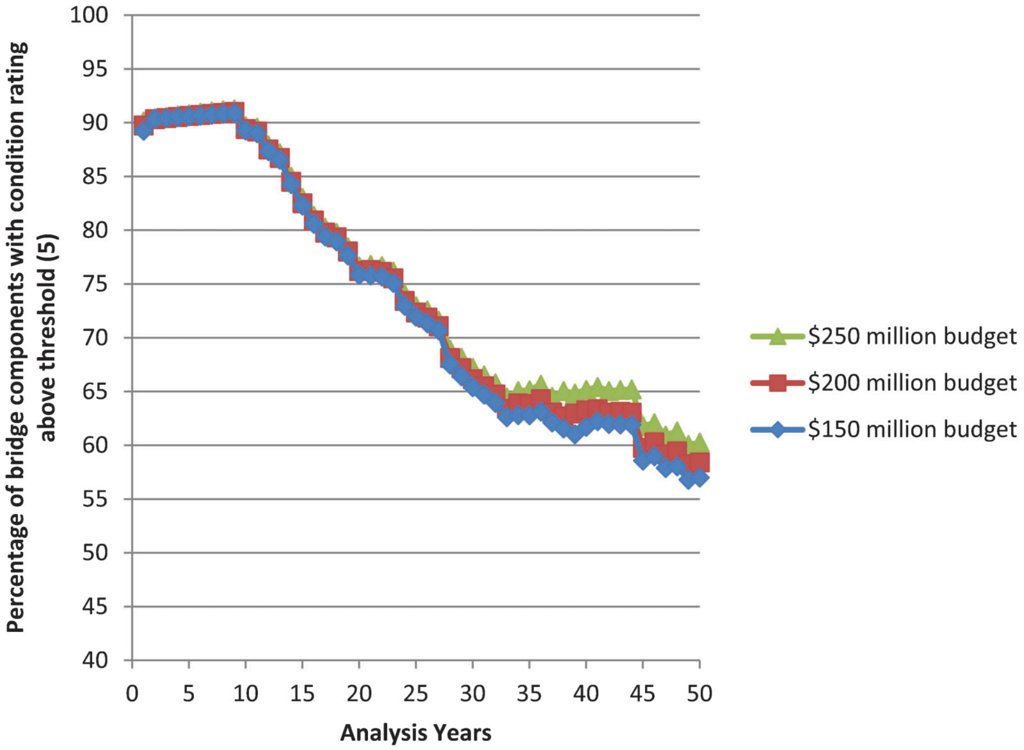


Figure 5.4 Comparison of budget levels for late maintenance strategy threshold analysis.

of the bridges will be forced to use bridges that are below performance standards. Equation 5.2 combines these three elements to evaluate the three different strategies.

$$\text{Strategy Index Function} = \frac{P_{\textit{above threshold}}}{3} + \frac{P_{\textit{rating greater than or equal to 6}}}{3} - \frac{P_{\textit{rating less than or equal to 2}}}{3} \quad (5.2)$$

Equation 5.2 is an index function. Each element contributes an equal amount (one third) to the overall index. $\mathrm{P}_{\text{rating less than or equal to 3}}$ is a negative index because the higher the percentage of bridges with ratings less than or equal to 3 is, the worse the strategy is performing. After calculating the index for each strategy, the strategy with the highest index will be the recommended strategy.

TABLE 5.3
Comparison of budget levels for late maintenance strategy threshold analysis (5 year increments)

Year	$150 million budget	$200 million budget	$250 million budget
5	90.6	90.6	90.8
10	89.3	89.4	89.7
15	82.3	82.5	83.0
20	75.8	76.2	76.6
25	72.0	72.4	72.9
30	65.4	66.2	67.2
35	62.8	63.9	65.1
40	61.7	63.3	65.2
45	58.6	59.8	61.8
50	57.0	58.4	60.3

Table 5.4 shows the results of this index analysis. For each budget level, the standard maintenance strategy has the highest index values, the early maintenance strategy has the second highest index values, and the late maintenance strategy has the lowest index values.

After performing the index analysis, it is recommended that the standard maintenance strategy be implemented. However the strategy should not be implemented exactly as programmed into BMRS. Because the standard maintenance strategy programmed into BMRS only contains five treatments, this strategy should be revised and tested in dTIMS before it is implemented. Once the standard maintenance strategy has been revised and tested in dTIMS, the revised version of this strategy can be implemented by INDOT.

TABLE 5.4
Index analysis for different strategies at different budget levels

Strategy	Budget level	Total index
Standard	$150 million	28.88118325
Standard	$200 million	33.00584349
Standard	$250 million	36.0581352
Early maintenance	$150 million	25.53779026
Early maintenance	$200 million	24.11652687
Early maintenance	$250 million	26.89269907
Late maintenance	$150 million	22.62462801
Late maintenance	$200 million	23.70127794
Late maintenance	$250 million	26.07718465

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APPENDIX A: ATTEMPTED TROUBLESHOOTING OF THE INDIANA BRIDGE MANAGEMENT SYSTEM (IBMS)

The Indiana Bridge Management System (IBMS) software package was originally developed at Purdue University. It has been used for several research projects, during which the software was modified by several different users. Most of these users have been graduate students who have moved on, but left no documentation of the changes they made. The researchers on this project tried to use IBMS to perform the analysis, but troubleshooting IBMS with little documentation became an enormous effort with no success after several months.

Several outside sources were consulted by researchers to try to get IBMS running properly. These sources included a graduate research assistant who worked on project SPR-3013: *Updating and Enhancing the Indiana Bridge Management System (IBMS)*, a JTRP web developer who had been involved in SPR-3013, and a graduate research assistant with industry experience in computer science. Although these people generously donated their time to the project, none of them was able to get IBMS to work properly.

There were several possible reasons why IBMS could not function properly. Some of the major challenges included finding the right computer and operating system for IBMS to run on; the input file structure for IBMS, and getting the output file to display correctly.

The first challenge was to find the right computer and operating system to run IBMS on. Because some of the problems with IBMS were difficult to solve, researchers acquired a version of the source code for IBMS to try to troubleshoot it. The version of the IBMS source code that was given to the researchers for this project was developed using an older version of Microsoft Visual Studio. When researchers attempted to open the project with a newer version of Visual Studio, there were some complications with converting the code into a new format. After unsuccessfully trying to get IBMS to run on 3 different newer computers, one solution that was attempted was using an older computer. An older computer that was running Microsoft Windows XP as the operating system (the operating system which the version of IBMS given to researchers was developed on) and an older version of Visual Studio was used to try to troubleshoot IBMS. However, even with this older computer, troubleshooting on IBMS was not successful.

Another challenge that had to be overcome was to get the input file for IBMS working properly. The input file that was used was a Microsoft Access database. This database needed to have a very specific set of tables. Additionally, the tables require a specific format for the data that they contain. With little to no documentation available, the process of figuring out the tables and the formatting of those tables was very time consuming, but eventually successful.

Once a proper input file was constructed, researchers had to attempt to troubleshoot the IBMS output from the source code. This process was tedious and required a great amount of time. The way that the source code for IBMS works is that it takes the data from the tables in the Microsoft Access Database and manipulates those tables until a final output file is constructed. Some of the manipulations include creating new tables; adding and removing columns from some tables; and changing the data in some cells of those tables. Because the source code has gone through many different users, many different statements in the source code manipulate the input file in many different ways. Because of the volume of these statements and the lack of documentation in the code as to what the statements actually do, troubleshooting these statements was a very tedious process. Eventually, after BMRS was developed, researchers concluded that enough time had been spent on troubleshooting IBMS, and because BMRS was available and functioning, a decision to abandon the use of IBMS for this project was reached.

APPENDIX B: BMRS USER'S GUIDE

You must have Java running on your computer in order to run the .jar file that executes the Bridge Management Research Software (BMRS).

The Bridge Management Research Software (BMRS) uses a bridge data input file that is constructed by the user. The data input file must be created separately, and it must be in the form of a Microsoft Excel spreadsheet. The format for this spreadsheet is shown in Figures B.1 and B.2. The order of the columns must be exactly the same as shown in these figures. The column headings must also be the same as given in these figures. The file format for this data input file must be the Microsoft Excel 97–2003 (.xls) format; other Microsoft Excel formats will not work. If a user has a Microsoft Excel file in another format (such as .xlsx), this file can be saved in the .xls file format, and BMRS will be able to use that file as the data input file as long as the column headings are correct.

There are several items in this data input file:

(1) Structure number. This item is field 008 in the NBI data dictionary (Federal Highway Administration, 2012).
(2) Different component condition ratings. BMRS requires a deck condition rating, superstructure condition rating, and substructure condition rating.

  - The deck condition rating is field 058 in the NBI data dictionary.
  - The superstructure condition rating is field 059 in the NBI data dictionary.
  - The substructure condition rating is field 060 in the NBI data dictionary.

(3) Most recent repair year. This item is field 106C in the NBI data dictionary. BMRS differentiates between the year the deck, substructure, and superstructure were last repaired. However, sometimes this data is not available on a component by component basis. In this case, it is recommended that the same NBI data item, field 106C be used for all components.

Once the bridge data input file has been constructed in Microsoft Excel, the user should open the provided .jar file to run BMRS. Figure B.3 shows the analysis period input screen. The length of the analysis period (in years) should be entered into the text box circled in Figure B.3.

The next user input item that is required is a budget. Figure B.4 shows the budget input screen. The budget values should be input into the circled text boxes. BMRS requires the budget to be input as two separate items for every year.

(1) Maintenance budget. This is entered into the text box labeled "enter budget for year x." This portion of the budget will be used only on the maintenance treatments that the user will define and enter in the screen shown in Figure B.6. (The format for maintenance treatments is given in Figure B.6. The user may enter as many or as few treatments as desired.)
(2) Replacement budget. This is entered into the text box labeled "enter replacement budget for year x." This portion of the budget will be used only on replacement treatments that the user will input in the screen shown in Figure B.5. (The format for replacement treatments is given in Figure B.5.)

Both budget values should be entered as integer values, without commas, decimals, or dollar signs. BMRS will not accept input with these characters, and will not allow the user to continue if any of these characters are entered as input. If the budget values are constant for every year of the analysis period, then a budget value need be entered only into the text box labeled "enter budget for year 1." By clicking the "copy values" button highlighted by the rectangle at the bottom of Figure B.4, the budget values for year 1 will be copied to all the other analysis years.

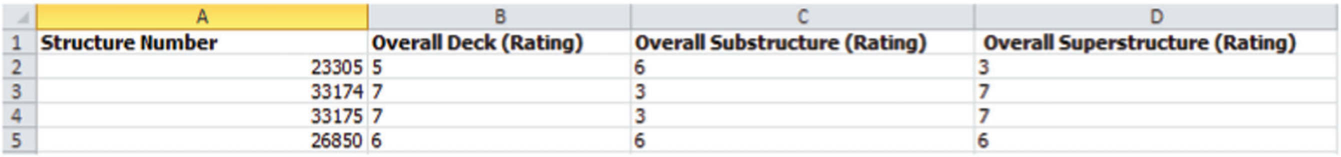
Figure B.5 shows the bridge replacement treatment input screen. BMRS performs bridge replacement treatments before bridge maintenance treatments. BMRS will perform these treatments for the bridges with the lowest individual component condition ratings until the bridge replacement budget has run out. (BMRS sorts the component condition ratings for all components of all bridges. The lowest component condition ratings will trigger a replacement treatment, in which all components of a treated bridge will receive a "performance jump.") This screen requires two user input items.

(1) Replacement cost. The text in this text box should be entered as integer values, without commas, decimals, or dollar signs. BMRS will not accept input with these characters.
(2) Resultant state. The condition rating which all the bridge components will be in if the replacement treatment is applied to the bridge. This represents the "performance jump" that the bridge components experience from the treatment.

The next user input item that BMRS requires is treatment data. Figure B.6 shows the input screen for one bridge treatment type. Treatments are entered as input one at a time. There are several components required for entering treatment input.

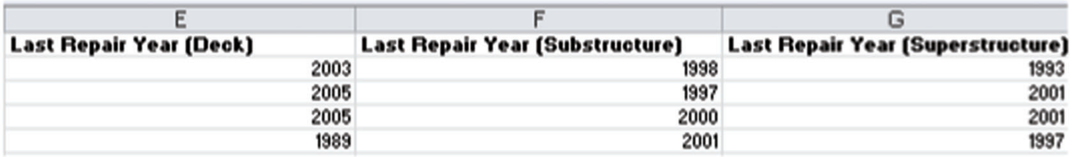
(1) The "treatment name" text box. The treatment name is text input, and any standard keyboard characters are accepted by BMRS, including numbers and symbols.
(2) The bridge component that the treatment applies to. The circled radio buttons give the choices for the bridge components. There are 3 radio buttons that the user can select from, one for each bridge component in the data input file.
(3) The "Enter treatment cost" text box. The text in this text box should be entered as integer values, without commas, decimals, or dollar signs. BMRS will not accept input with these characters.
(4) The "Enter Lower Bound," "Enter Upper Bound," and "Enter Resultant State" drop down boxes represent the boundary conditions for the treatment. These items are highlighted by the rectangle in this figure.

  - The lower bound is the minimum condition rating at which that specific treatment is considered feasible. If the bridge component condition is lower than the minimum condition rating, that treatment will not be used on the bridge.
  - The upper bound is the maximum condition rating at which that treatment will be applied. If the bridge component condition is higher than the maximum condition rating, then that treatment will not be used on the bridge.
  - The resultant state is the condition rating which the bridge component will be in if the treatment is applied to the component. This represents the "performance jump" that the bridge component experiences from the treatment.



	A	B	C	D
1	Structure Number	Overall Deck (Rating)	Overall Substructure (Rating)	Overall Superstructure (Rating)
2	23305	5	6	3
3	33174	7	3	7
4	33175	7	3	7
5	26850	6	6	6

Figure B.1 BMRS input Excel file, columns A through D.



E	F	G
Last Repair Year (Deck)	Last Repair Year (Substructure)	Last Repair Year (Superstructure)
2003	1998	1993
2005	1997	2001
2005	2000	2001
1989	2001	1997

Figure B.2 BMRS input Excel file, columns E through G.

After the first treatment is entered, the user may want to put in more treatments for consideration. To add another treatment, the user simply has to use the "Add More" button at the bottom of the screen. This button is highlighted with the arrow in Figure B.6. Once all the desired treatments have been added, the "Finish" button at the bottom of the screen will move BMRS to the next screen.

The next required user input is the performance thresholds. A performance threshold is used as a performance measure for the inventory of bridges assembled in the Microsoft Excel input file. For each year in the analysis period, BMRS will determine how many bridges have a component rating above or below this component threshold. This performance will be displayed as the percentage of bridges above the performance threshold. The possible values for performance thresholds are selected from the circled drop down boxes in Figure B.7. These values are the NBI component condition ratings for each bridge component. The performance threshold can be selected individually for each bridge component. Once all performance thresholds have been selected, the user clicks the "Analyze" button at the bottom of the screen. This button is highlighted with the arrow in Figure B.7.

Once the "Analyze" button is clicked, BMRS will prompt the user to select an input file. This input file should be the same Microsoft Excel input file created earlier by the user. The user must navigate to the location where this file has been saved on his or her computer. Figure B.8 shows an example of the selection screen where the input file has been stored in a folder named "BMRS input files." After the user clicks on this file to select it, clicking on the circled "Open" button will cause BMRS to run and produce an output file.

After the "Open" button is clicked, the user will be prompted to save the output file BMRS creates. This file should be saved as .xls file. Figure B.9 shows the screen for saving this output file. The user selects the file name and save location of the newly created output file. (By default, BMRS will overwrite the input file with

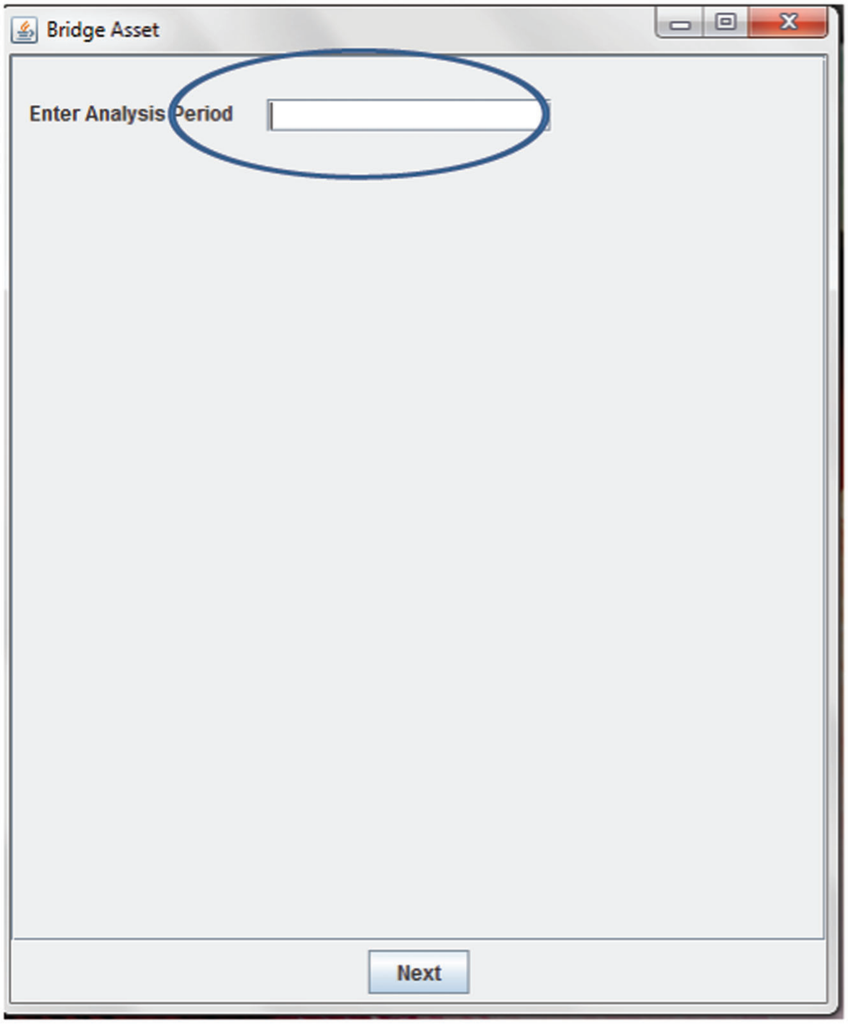
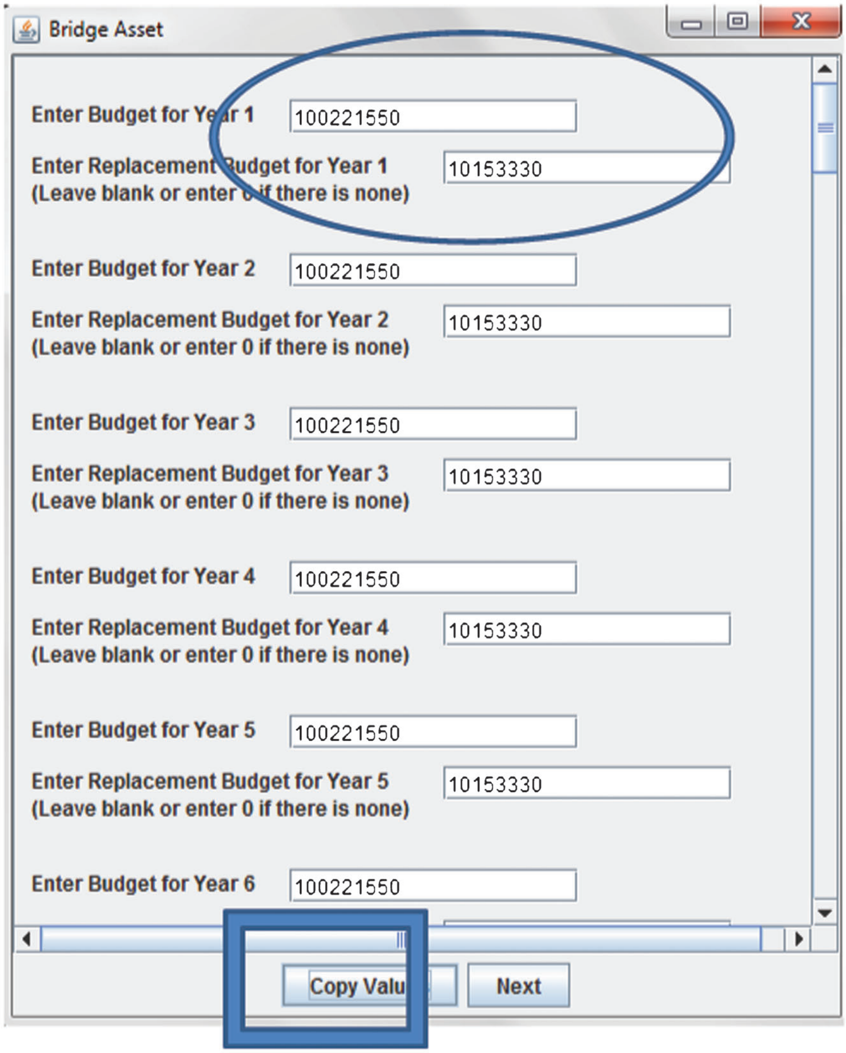


Figure B.3 Analysis period input screen.

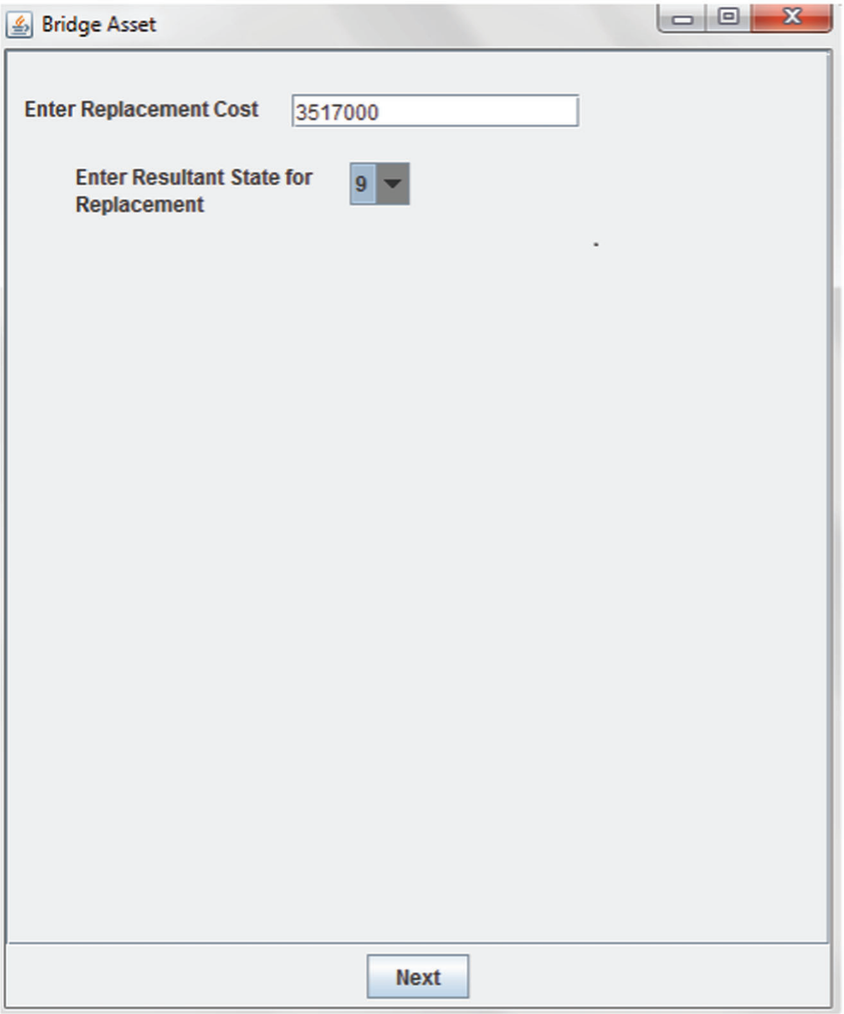


Enter Budget for Year 1: 100221550
Enter Replacement Budget for Year 1 (Leave blank or enter 0 if there is none): 10153330
Enter Budget for Year 2: 100221550
Enter Replacement Budget for Year 2 (Leave blank or enter 0 if there is none): 10153330
Enter Budget for Year 3: 100221550
Enter Replacement Budget for Year 3 (Leave blank or enter 0 if there is none): 10153330
Enter Budget for Year 4: 100221550
Enter Replacement Budget for Year 4 (Leave blank or enter 0 if there is none): 10153330
Enter Budget for Year 5: 100221550
Enter Replacement Budget for Year 5 (Leave blank or enter 0 if there is none): 10153330
Enter Budget for Year 6: 100221550

Figure B.4 BMRS budget input screen.

the output file. If the user wants to perform multiple runs with an input file, the user can simply rename the output file, so that the input file will be saved.) Once the user has selected a name and location for the output file, clicking the circled "Save" button will save the BMRS output file for future use. In Figure B.9, the file has been named "bmrs_output_1.xls" and the location selected is a folder named "BMRS output files."

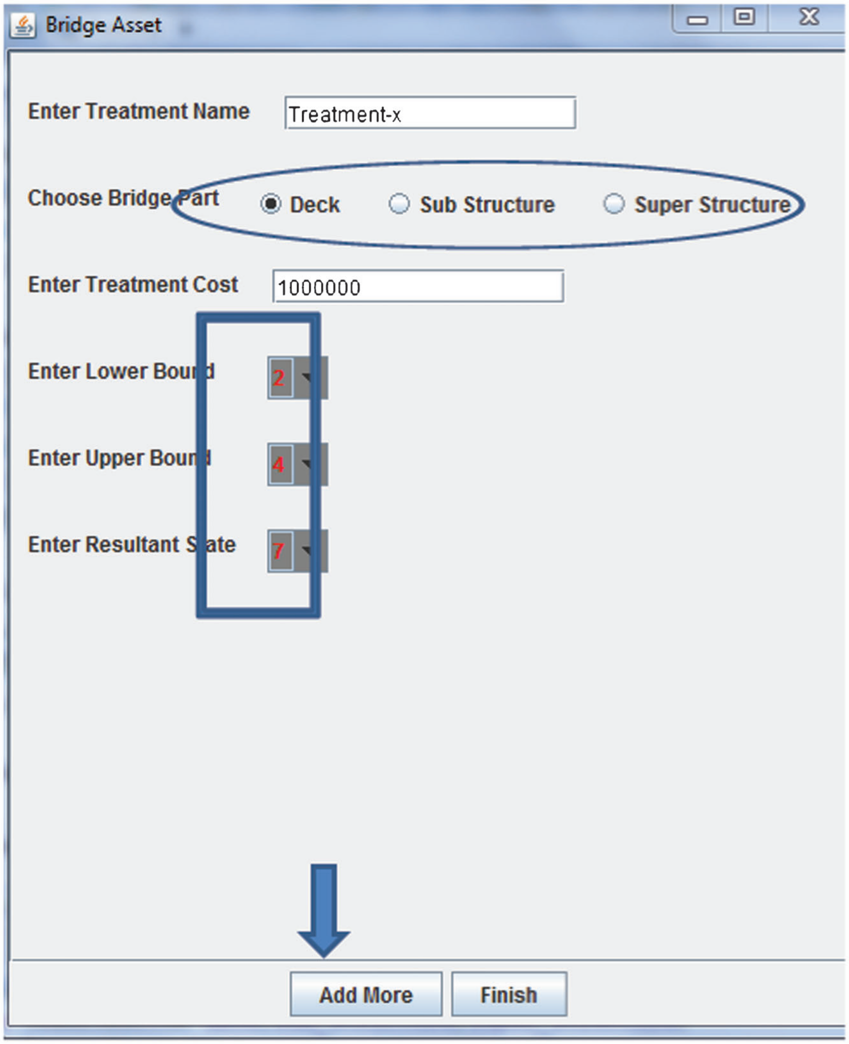
Once the output file is saved, the user can open it. Figure B.10 shows an example of a BMRS output file. The circled values indicate the percentages of bridge components above the performance threshold. In this example the performance threshold is 5 for all components. BMRS gives these results for each year of the analysis period, one year at a time. Each result is stored in a different tab in the output file. The box in Figure B.10 indicates the tabs for the different analysis years. The output file does not label the columns of data. They are always the same, and Table B.1 gives the Excel column and the corresponding label for that column.



Enter Replacement Cost 3517000

Enter Resultant State for Replacement 9

Figure B.5 Bridge replacement treatment input screen.



Enter Treatment Name: Treatment-x

Choose Bridge Part: ● Deck ○ Sub Structure ○ Super Structure

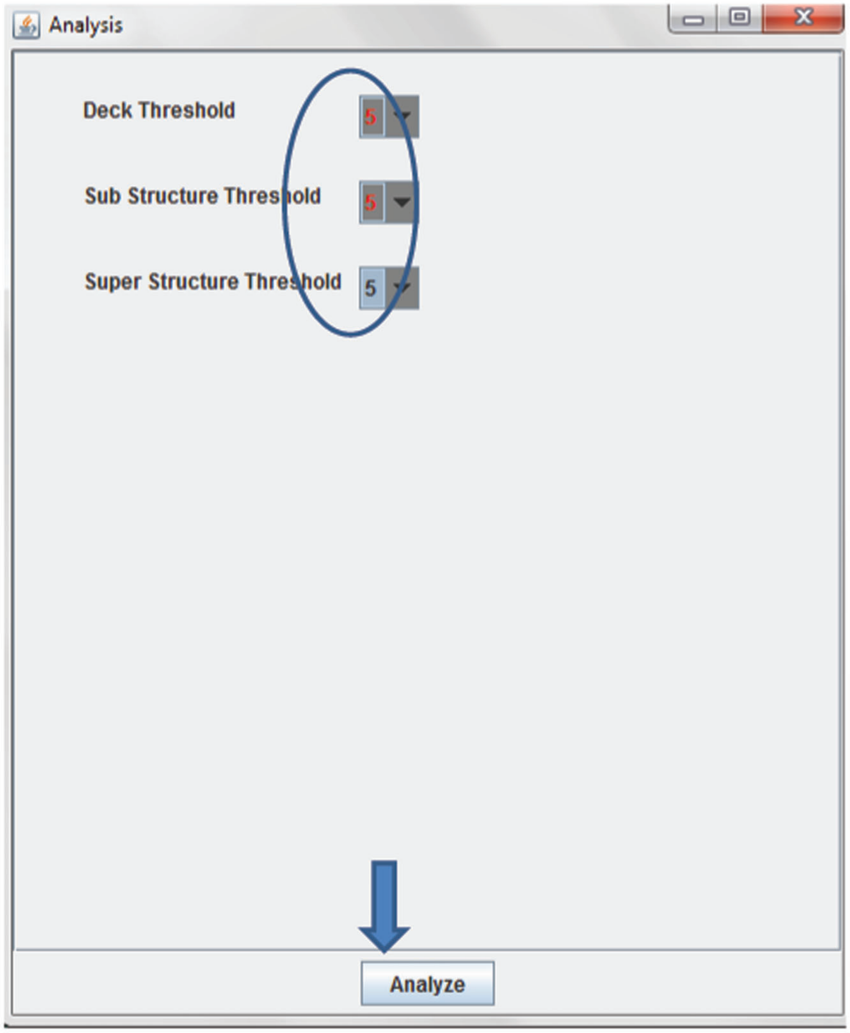
Enter Treatment Cost: 1000000

Enter Lower Bound: 2

Enter Upper Bound: 4

Enter Resultant State: 7

Figure B.6 Bridge maintenance treatment input screen.

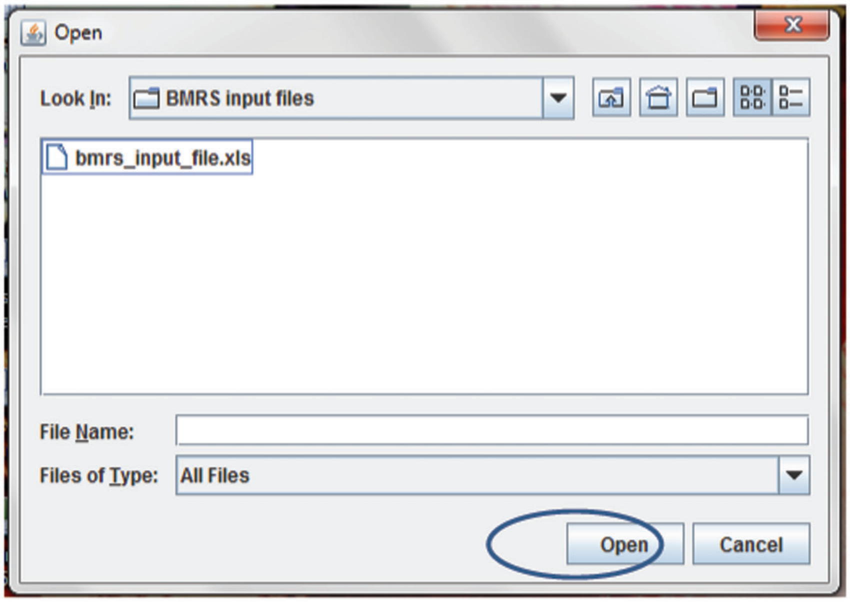


Deck Threshold 5

Sub Structure Threshold 5

Super Structure Threshold 5

Figure B.7 Threshold input screen.



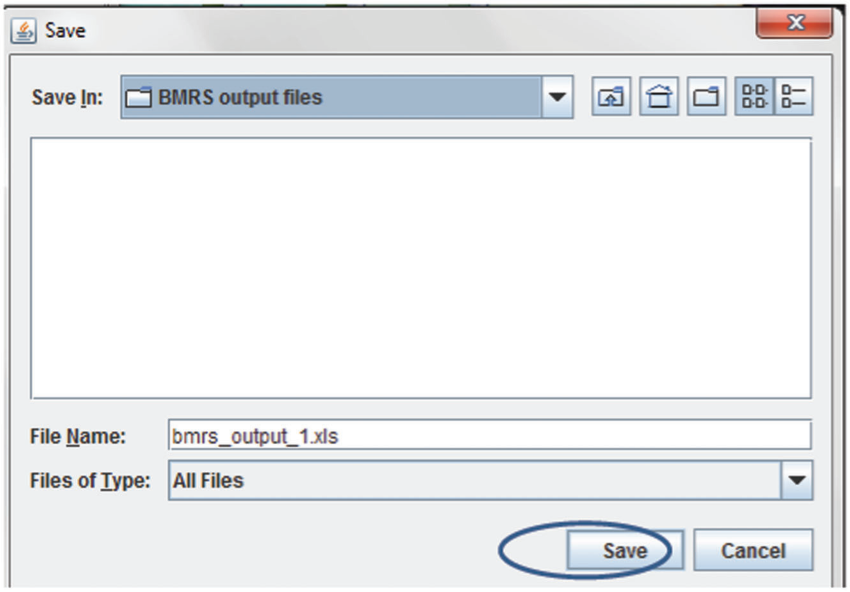
Look In: BMRS input files

bmrs_input_file.xls

File Name:

Files of Type: All Files

Figure B.8 BMRS input file selection screen.

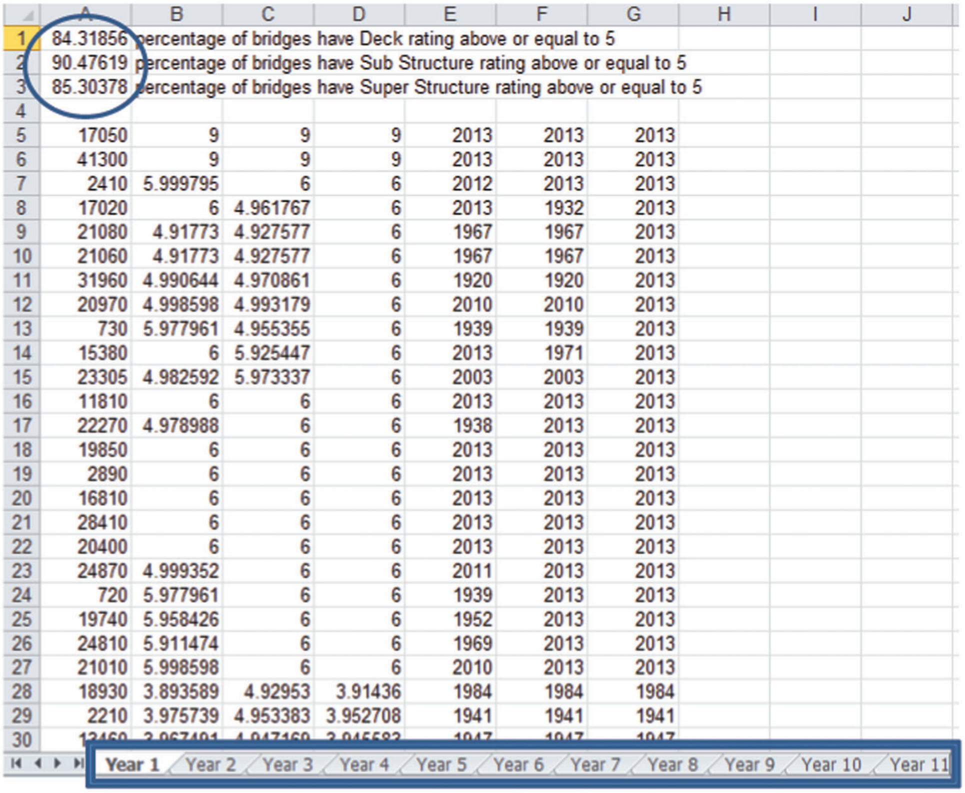


Save In: BMRS output files

File Name: bmrs_output_1.xls

Files of Type: All Files

Figure B.9 BMRS output file save screen.



	A	B	C	D	E	F	G	H	I	J
1	84.31856	percentage of bridges have Deck rating above or equal to 5								
2	90.47619	percentage of bridges have Sub Structure rating above or equal to 5								
3	85.30378	percentage of bridges have Super Structure rating above or equal to 5								
4										
5	17050	9	9	9	2013	2013	2013			
6	41300	9	9	9	2013	2013	2013			
7	2410	5.999795	6	6	2012	2013	2013			
8	17020	6	4.961767	6	2013	1932	2013			
9	21080	4.91773	4.927577	6	1967	1967	2013			
10	21060	4.91773	4.927577	6	1967	1967	2013			
11	31960	4.990644	4.970861	6	1920	1920	2013			
12	20970	4.998598	4.993179	6	2010	2010	2013			
13	730	5.977961	4.955355	6	1939	1939	2013			
14	15380	6	5.925447	6	2013	1971	2013			
15	23305	4.982592	5.973337	6	2003	2003	2013			
16	11810	6	6	6	2013	2013	2013			
17	22270	4.978988	6	6	1938	2013	2013			
18	19850	6	6	6	2013	2013	2013			
19	2890	6	6	6	2013	2013	2013			
20	16810	6	6	6	2013	2013	2013			
21	28410	6	6	6	2013	2013	2013			
22	20400	6	6	6	2013	2013	2013			
23	24870	4.999352	6	6	2011	2013	2013			
24	720	5.977961	6	6	1939	2013	2013			
25	19740	5.958426	6	6	1952	2013	2013			
26	24810	5.911474	6	6	1969	2013	2013			
27	21010	5.998598	6	6	2010	2013	2013			
28	18930	3.893589	4.92953	3.91436	1984	1984	1984			
29	2210	3.975739	4.953383	3.952708	1941	1941	1941			
30										

Figure B.10 BMRS output file.

TABLE B.1
BMRS output file column headings

Excel column letter	Column heading
A	Structure Number
B	Deck Condition Rating
C	Substructure Condition Rating
D	Superstructure Condition Rating
E	Last Repair Year (Deck)
F	Last Repair Year (Substructure)
G	Last Repair Year (Superstructure)

VOLUME II

EMPLOYING ASSET MANAGEMENT TO CONTROL COSTS AND SUSTAIN HIGHWAY LEVELS OF SERVICE: PAVEMENT AND MOBILITY MANAGEMENT

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. STUDY SCOPE, OBJECTIVES, AND METHODS

An ideal highway asset management program involves a systematic process of cost-effectively maintaining, upgrading and operating physical highway assets. It combines fundamental engineering principles with sound business practices and economic principles for managing highway infrastructure assets, and it generally considers pavements, bridges and other facilities to enhance traffic mobility and safety. The use of performance measures is an integral component of the infrastructure management process. The common measures include:

- International roughness index (IRI), pavement condition rating (PCR) and other indicators for pavement infrastructure.
- National Bridge Inventory (NBI) Rating, load rating and other indicators for structures.
- Volume-capacity ratio, travel time or speed, delay and other indicators for traffic mobility.
- Crash rates, number of crashes, and other indicators of highway safety.

Highway asset performance measures are used for a variety of purposes, including triggering placement of a highway segment on a candidate list to receive restorative treatment (which can be a pavement rehabilitation treatment, highway capacity-increasing project, safety enhancement or others).

The selection of performance measure trigger values to address asset condition deficiencies at the project-level has a profound impact on the intra-asset and inter-asset conditions at the network level. The choice of trigger values affects the ranking, prioritizing, programming and financing of restorative activities.

The purpose of this research project was to analyze the impacts of changing the trigger standards of certain asset condition restorative projects and varying the available budget on the network-level asset condition for the pavement, mobility, bridge and safety asset classes.

The feasibility of creating a Budget-Constrained System Performance (BCSP) Curve, as shown in Figure 1.1, to facilitate the network-level condition analysis for each of the four major asset classes was examined. For each performance category (pavement condition, bridge condition, mobility, and safety), a system performance curve could theoretically be built to show the level of system performance that could be expected for any budget level and trigger standard. The vertical axis could be used to either represent an appropriate average measure of performance for the asset category being analyzed, or it could be the percentage of the asset that meets a desired performance threshold.

The HPMS 2009 dataset and the HERS-ST software were selected to carry out the analysis for the pavement and mobility asset areas in this project. The software operation process is summarized in Chapter 2, and the modification of various settings is documented in appropriate locations in Chapters 2, 3, and 4.

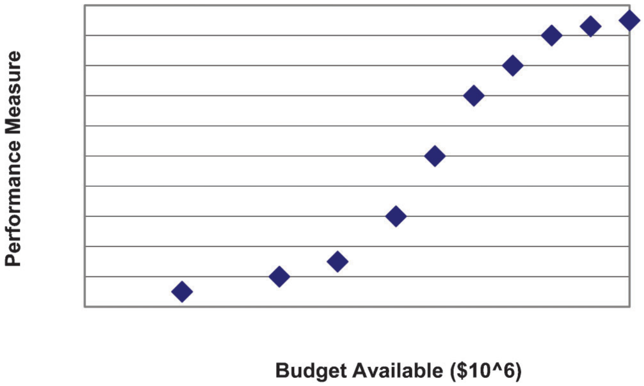


Figure 1.1 Budget-constrained system performance curve concept.

To provide a back drop for the study results, there is a brief discussion of the performance measures that are being developed or currently being used to reflect conditions for the pavement, mobility and safety asset classes. There is also a mention of the recent trend to convert asset performance data into level of service information that can be understood by non-engineers.

A. Pavement management. There is extensive literature regarding the life cycle of pavement alternative treatments and their timing, and the quest to optimize resource allocations in pavement management (Khurshid et al., 2011; Li & Madanat, 2002; Sathaye & Madanat, 2012; Wang & Zaniewski, 1996). Figure 1.2 shows the concept of optimal timing of restorative treatments to ensure good service life for a pavement section. The treatment timing for each roadway segment depends on loading by traffic, budget constraints, and agency philosophy.

It can be noted that the timing of the pavement rehabilitation decision has a higher effect on the service life of the asset than the timing of the pavement preventive maintenance decision (Martin & Thoresen, 1998). Therefore, the impact of changing "moderate strength" and "heavy strength" pavement rehabilitation trigger values on the future pavement network-level condition was examined.

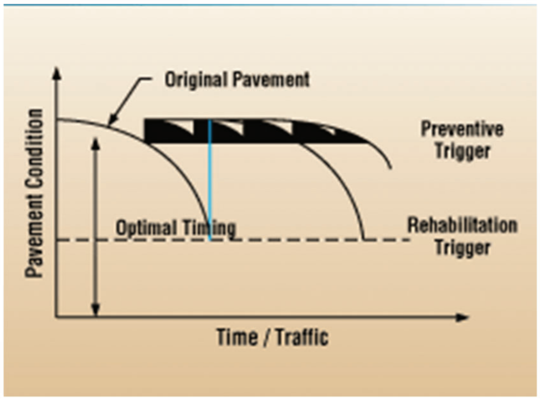


Figure 1.2 Decision points in pavement management.

The research community has recently cited the development of pavement functional and structural adequacy indices as a priority to enhance performance measurement and tracking at the network-level and some states have funded research to develop a pavement structural index (Flora et al., 2010; Bryce et al., 2013).

Additionally, the HPMS 2010 reassessment has now required that, in addition to roughness data, distress data such as rutting, faulting, and cracking be collected for sample sections (FHWA Office of Highway Policy Information, 2010). Although most state DOTs already collect distress information, it should be noted that the development of pavement adequacy indices to supplement roughness information in identifying and prioritizing pavement project needs at the network-level also necessitates the creation of condition forecasting models for these indices to predict how they change over time in response to deterioration or treatment.

For the pavement asset class, the impact of changing the pavement moderate and heavy rehabilitation project triggers and the budget available on the network-level pavement roughness condition was examined for the State Urban road network, State Rural Arterials, and the Federal-Aid Urban road network. The results are contained in Chapter 3. The performance measure used for the pavement asset area was percent of roadway miles meeting certain IRI condition threshold values.

B. Mobility management. Regarding highway mobility, the Highway Capacity Manual (TRB, 2000) offers a standard procedure for establishing a Level of Service (LOS) based on metrics such as density (vpm), speed and vehicle delay. However, Choocharukul et al. (2004) demonstrated that the HCM-based LOS may not always match the perceptions of highway users.

Mobility performance of the roadway network can be expressed using many different measures, such as the ones identified below within the three different dimensions of Quality, Accessibility, and Capacity Utilization (McLeod, 2008).

- Quality: user satisfaction with the transportation facility
    - Percent of travel meeting a certain Level of Service criteria
    - Travel time reliability
    - Duration of congestion
- Accessibility: ease with which travelers can access the transportation facility in the ultimate pursuit of a destination
    - Proximity to major transportation hubs
    - Proximity to activity centers
- Capacity Utilization: quantity of operations relative to capacity; indicates resource use efficiency for the transportation facility
    - Percent of congested miles
    - Percent of congested travel

An example of a measure that can capture users' perception of highway mobility is travel time reliability. The SHRP 2 L08 research project titled "Incorporation of Travel Time Reliability into the Highway Capacity Manual" seeks to reduce the gap between the HCM-based LOS and highway users' experience of the mobility condition.

Additionally, SHRP 2 provides guidance on monitoring travel time reliability performance (L02), determining the impact of reliability mitigation strategies (L03), and incorporating reliability performance measures in the transportation planning and programming process (L05).

The HPMS 2009 database used in the analysis for this project contains a peak hour volume capacity ratio value for each road segment. Therefore, this research study used the "Capacity Utilization" performance measures to construct budget-constrained performance curves for the mobility asset for the State Urban road network and the Federal-Aid Urban road network. The two measures used to develop the curves were: (1) the percent of roadway miles experiencing congestion during the peak hour, and (2) the percent of VMT traveling through roads that experience congestion during the peak hour. The results are shown in Chapter 4.

C. Safety management. The most common metrics for highway safety are counts of fatalities, personal injuries, and property damage crashes. For purposes of analysis, these counts are converted into rates such as crashes per million entering vehicles or crashes per hundred million vehicle miles. INDOT uses the annual *Five Percent Report* to identify the roadways and intersections with the worst crash rates for possible countermeasure implementation funded by the Highway Safety Improvement Program. Additionally, indices that reflect the safety condition of roadway segments can be developed and used to enhance decision-making in prioritizing safety improvement projects.

For this research project, the use of horizontal and vertical alignment adequacy measures as reported in the HPMS 2009 data were examined to determine if they can be used to enhance decision-making in implementing safety restorative projects.

As can be seen in Chapter 2, most urban road sections have no reported alignment adequacy information. Additionally, HPMS data does not contain crash rate information and there is no available information on intersection safety adequacy. This limits the usefulness of the alignment adequacy information.

Furthermore, the process by which HERS-ST software estimates the influence of alignment correction (safety restorative action) on network-level roadway safety is flawed; the overall crash rate as well as fatality and severe injury rates are calculated for each functional class based purely upon the alignment adequacy measures and roadway geometry, without calibration to the currently observed metrics. Therefore, it was determined that development of budget-constrained system performance curves for safety management is currently infeasible, but could become feasible if the results of recent JTRP research efforts (SPR-3315 and SPR-3640) are utilized and extended in the future.

The safety screening tool developed for Indiana through SPR-3315 can identify high crash locations and screen the safety performance by geographical scope, roadway element, crash type criteria, and roadway feature (Tarko et al., 2012). The backbone data contained in the tool consists of Indiana road links, intersections, ramps, bridges, and geometric inventory information. Additional data was integrated, including traffic flow information, weather data, land use and demographic data from traffic analysis zones, boundary layer for counties and cities, and crash data.

The tool could theoretically be linked up to a safety asset management software module for the purpose of evaluating network-level safety performance of the highway system in response to funding to implement countermeasures designed to address safety issues. This newly developed tool could be used in conjunction with the findings of the currently ongoing SPR-3640 research study that is developing a geometry sufficiency index to evaluate the geometric adequacy of road cross-sections based on documented safety and speed effects. One of the purposes of developing this index is to evaluate current deficiencies throughout the network and to aid in prioritizing safety improvement projects.

D. User-based service levels and public outreach. A growing number of state agencies are incorporating measures of customer satisfaction with system performance and reporting the values of these measures to the public. The Washington State DOT maintains a list of performance reporting practices of states DOTs online at http://www.wsdot.wa.gov/accountability/publications/library.htm.

As public agencies have become more business oriented, most have felt the need to be more in tune with and responsive to their customers, the traveling public. These customers have become much more demanding in the level of service they expect from the agencies and in having their views meaningfully taken into account in decisions ranging from program priorities to project design to maintenance standards.

The NCHRP 608 report (Brinckerhoff et al. 2008) has recommended that measures of customer satisfaction be taken into account in the process of setting condition targets and the NCHRP 677 report (Dye, 2010) extends that recommendation with guidance for state DOTs to use customer surveys as forums to explain to users and various stakeholders the performance metrics that are used to evaluate roadway condition and how the metrics are used to prioritize highway improvement projects and actions.

The goals of the NCHRP 20-74A study (Dye, 2010) that produced the NCHRP 677 report were to:

- Formulate descriptions of performance ratings that are meaningful to stakeholders.
- Develop a recommended scale and definitions of service levels [that] address concerns of highway users, transportation agencies, and other stakeholders.
- Define consistent and specific thresholds for measures that define service levels and how thresholds (e.g., of quality or acceptability) are determined with respect to each service-level indicator.
- Develop a template that can be used to assess, analyze, and report system performance at the state or local levels. Include a methodology for addressing weighting among asset groups, urban or rural character, and other relevant factors to produce a composite service level for the system being analyzed.

The study documented the state of practice in state DOTs' collection of asset condition information. Interviews with several state DOTs were carried out to determine the consensus of asset elements for which data is collected. This consensus was used to propose a list of elements for which level of service information could be generated from performance data collected. The list is shown in Figure 1.3.

Chapter 4 of the NCHRP 677 report features a template that demonstrates how the asset performance information can be converted into level of service information reflected in "report card" format. A snapshot of this template can be seen in Figure 1.4.

The service-level threshold numbers shown should reflect if the assets are functioning as designed to meet asset preservation, mobility, and safety objectives. State DOTs using the proposed template should use their judgment to change the numbers and/or can rely on customer surveys to calibrate these numbers through correlation of customer opinion and asset condition data collected by the agency.

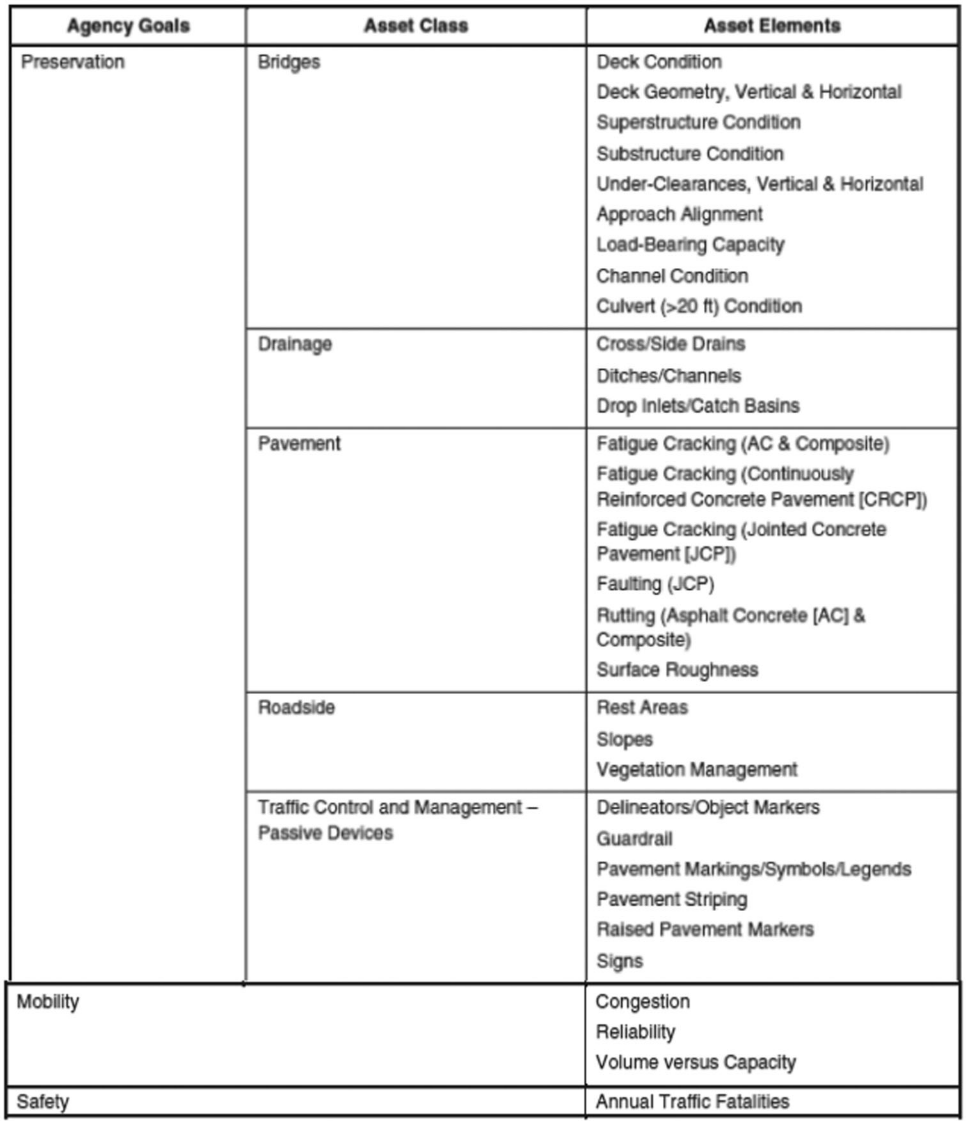
Asset performance information reported in a level of service format can be tracked from year to year, and the observed trends can be matched against expenditure levels. The template can be used to facilitate communication of highway performance condition with policymakers and other stakeholders to support critical funding needs, resource-allocation decisions, and demonstrate accountability in highway performance management.

2. METHODOLOGY

2.1 HERS-ST Basic Software Run Process

The Federal Highway Administration website contains documentation on the details of the HERS-ST software operation, its features, its settings and how to interpret the output at http://www.fhwa.dot.gov/infrastructure/asstmgmt/hersrprep.cfm. This section summarizes the software process used in generating improvement projects and the impact of implemented projects. The system conditions of the State Rural Arterials, State Urban roads, and Federal-Aid Urban roads in 2009 as reported in the HPMS dataset are used as input.

The HERS-ST software functioning process is shown in Figure 2.1. The process begins with the user providing an input of HPMS (Highway Performance Monitoring System) data for highway sections. HPMS data are data reported by state departments of transportation (DOTs) to the Federal Highway Administration (FHWA) to



Agency Goals	Asset Class	Asset Elements
Preservation	Bridges	Deck Condition
		Deck Geometry, Vertical & Horizontal
		Superstructure Condition
		Substructure Condition
		Under-Clearances, Vertical & Horizontal
		Approach Alignment
		Load-Bearing Capacity
		Channel Condition
		Culvert (>20 ft) Condition
	Drainage	Cross/Side Drains
		Ditches/Channels
		Drop Inlets/Catch Basins
	Pavement	Fatigue Cracking (AC & Composite)
		Fatigue Cracking (Continuously Reinforced Concrete Pavement [CRCP])
		Fatigue Cracking (Jointed Concrete Pavement [JCP])
		Faulting (JCP)
		Rutting (Asphalt Concrete [AC] & Composite)
		Surface Roughness
	Roadside	Rest Areas
		Slopes
		Vegetation Management
	Traffic Control and Management – Passive Devices	Delineators/Object Markers
		Guardrail
		Pavement Markings/Symbols/Legends
		Pavement Striping
		Raised Pavement Markers
		Signs
Mobility		Congestion
		Reliability
		Volume versus Capacity
Safety		Annual Traffic Fatalities

Figure 1.3 List of roadway elements for which performance data can be converted to level-of-service information (Dye, 2010).

provide information on the extent, condition, performance, use, and operating characteristics of their state highway network. The reported data items include geometric inventory, pavement condition, and mobility condition.

2.2 HPMS Data Sampling

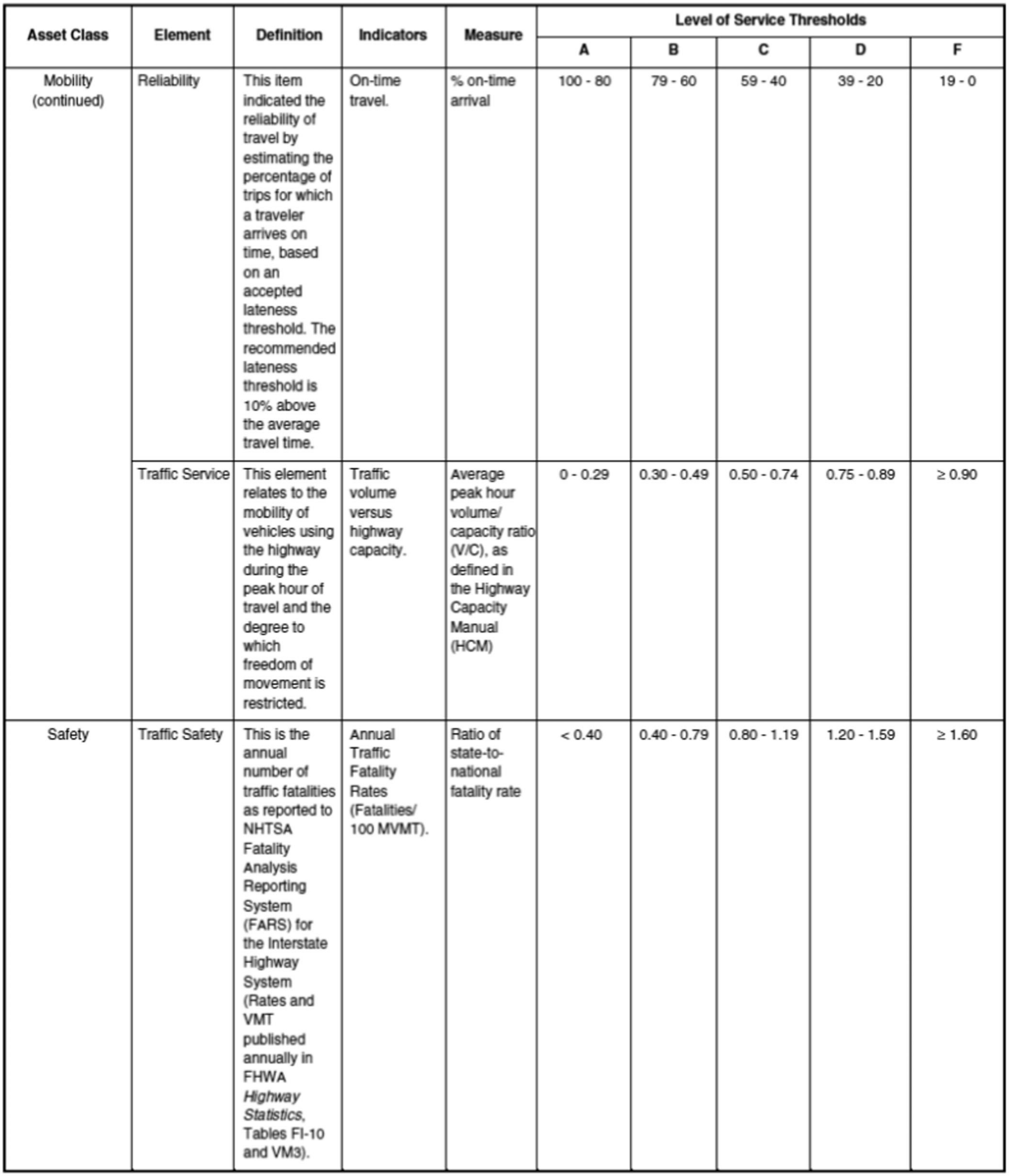
The analysis results for the State-Owned Rural System exclude the Rural Major Collector system because HPMS data has a limited number of sampling miles for the Rural Major Collector roads. Table 2.1 shows that 4593 miles of Rural Major Collectors are represented by only 285 miles of HPMS sample sections for the State-Owned Rural System.

Therefore, the analysis results of the State-Owned Rural System are limited to reporting the condition of the State-Owned Arterial System by spending various amounts of money on only State-Owned Arterials. In other words, the State-Owned Rural Major Collectors, unlike the State-Owned Rural Arterials, are given no funding in this HERS-based analysis and their aggregate condition 20 years later is not reported.

The data sampling issue was not present for the State-Owned Urban Network or the Federal-Aid Urban Network, as can be seen in the “Sampling Percent” rows of Tables 2.1 and 2.2.

2.3 Initial Characteristics and Conditions of the State Urban, State Rural Arterial, and Federal-Aid Urban Road Networks

Tables 2.3–2.5 show the initial VMT (2009) and final VMT (2029) on the State Urban roads, State Rural Arterials, and Federal-Aid Urban roads, respectively, as contained in the HPMS 2009 Indiana data file.



Asset Class	Element	Definition	Indicators	Measure	Level of Service Thresholds				
					A	B	C	D	F
Mobility (continued)	Reliability	This item indicated the reliability of travel by estimating the percentage of trips for which a traveler arrives on time, based on an accepted lateness threshold. The recommended lateness threshold is 10% above the average travel time.	On-time travel.	% on-time arrival	100 - 80	79 - 60	59 - 40	39 - 20	19 - 0
	Traffic Service	This element relates to the mobility of vehicles using the highway during the peak hour of travel and the degree to which freedom of movement is restricted.	Traffic volume versus highway capacity.	Average peak hour volume/ capacity ratio (V/C), as defined in the Highway Capacity Manual (HCM)	0 - 0.29	0.30 - 0.49	0.50 - 0.74	0.75 - 0.89	≥ 0.90
Safety	Traffic Safety	This is the annual number of traffic fatalities as reported to NHTSA Fatality Analysis Reporting System (FARS) for the Interstate Highway System (Rates and VMT published annually in FHWA *Highway Statistics*, Tables FI-10 and VM3).	Annual Traffic Fatality Rates (Fatalities/ 100 MVMT).	Ratio of state-to-national fatality rate	< 0.40	0.40 - 0.79	0.80 - 1.19	1.20 - 1.59	≥ 1.60

Figure 1.4 Snapshot of level-of-service information template (Dye, 2010).

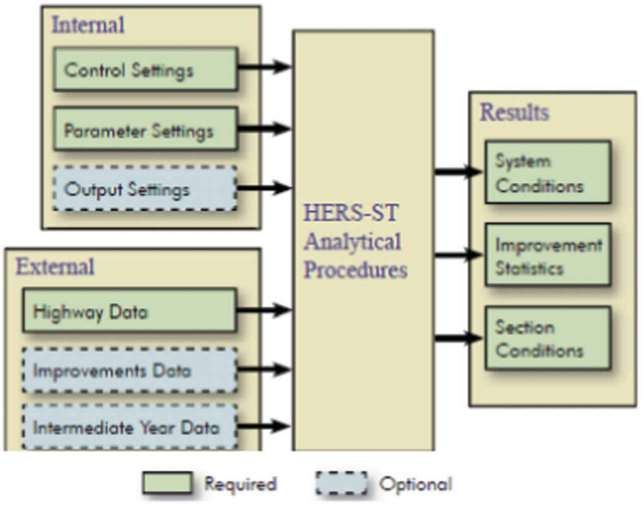


Figure 2.1 Overview of HERS-ST process (FHWA Office of Asset Management, 2009).

Tables 2.6–2.8 show the initial pavement roughness condition for the State Urban roads, the State Rural Arterials, and Federal-Aid Urban roads.

Tables 2.9–2.14 show the initial peak-hour mobility condition of the State Urban, the State Rural Arterial and the Federal-Aid Urban road networks, by number of miles and by VMT, respectively. As illustrated by Tables 2.10 and 2.13, the State Rural Arterials do not demonstrate a congestion problem during the peak hour.

The HPMS dataset contains two data items that represent the safety condition of a road segment. The data items are the horizontal and the vertical geometric alignment adequacy ratings. Tables 2.15 and 2.16 (FHWA Office of Highway Policy Information, 2005) show the meaning of these ratings.

Tables 2.17 and 2.18 show the horizontal and vertical geometric alignment adequacy at the network-level for State Urban roads. It can be seen that the HPMS dataset is missing information on most of the segments of that road network.

Tables 2.19 and 2.20 show the horizontal and vertical geometric alignment adequacy at the network-level for State Rural Arterials.

Tables 2.21 and 2.22 show the horizontal and vertical geometric alignment adequacy at the network-level for Federal-Aid Urban roads. It can be seen that the HPMS dataset is missing information on most of the segments of that road network.

2.4 HERS-ST Analysis Run Settings

After the data input step, the user modifies the Control Settings. Control Settings include options for specifying the objective function for maintaining the highway network. The software user can specify implementation of maximizing the benefit with a constrained budget or minimizing cost to maintain a particular economic performance benchmark. After the software user adjusts Control Settings, the Parameter

TABLE 2.1
State-Owned Highway Network center-line miles and the corresponding HPMSsample sections' center-line mile length (FHWA OHPI: Highway Statistics, 2009)

	Rural					Urban						
	Interstate	Other principal Arterial	Minor Arterial	Major Collector	Total Rural	Interstate	Expressway	Other principal Arterial	Minor Arterial	Major Collector	Total Urban	Total
Total Miles in Indiana's State Highway Network	694	1593	1981	4593	8861	460	153	1378	495	26	2512	11373
Number of Miles Represented by HPMS Sample Sections	324	598	384	285	1591	238	79	376	51	3	747	2338
Sampling Percent	47%	38%	19%	6%	18%	52%	52%	27%	10%	12%	30%	21%

TABLE 2.2
Federal-Aid Highway Network Center-line Miles and the corresponding HPMSSample Sections' Center-line Mile length (FHWA OHPI: Highway Statistics, 2009)

	Rural					Urban						
	Interstate	**Other principal Arterial**	**Minor Arterial**	**Major Collector**	**Total Rural**	**Interstate**	**Expressway**	**Other principal Arterial**	**Minor Arterial**	**Major Collector**	**Total Urban**	**Total**
Total Miles in Indiana's State Highway Network	694	1593	2063	10002	14352	460	164	1862	2981	3164	8631	22983
Number of Miles Represented by HPMS Sample Sections	324	598	392	397	1711	238	84	485	341	361	1509	3220
Sampling Percent	47%	38%	19%	4%	12%	52%	51%	26%	11%	11%	17%	14%

Settings can be adjusted. Parameter Settings include Deficiency Standards and Improvement Cost information. The deficiency standards and improvement costs can be modified to vary by functional class.

2.4.1 Control Settings' Options

There are two main options to choose from when setting the objective for the HERS run.

- Minimum improvement cost as constrained by performance Uses:
  - Calculate Cost to Improve Scenario—upper limit of investment in economically justifiable projects; implement all improvement with minimum Benefit Cost Ratio (BCR > some number).
  - Calculate Cost to Maintain Scenario—level of investment to maintain a particular economic performance benchmark (user cost per VMT).
- Maximize benefits as constrained by available funds—maximize future benefits (reductions in future costs incurred by the user such as vehicle operating, crash cost, and travel time cost) as a result of implementing a project. *This setting was used for the analysis in this report.*

2.4.2 Deficiency Identification

The Parameter deficiency standards are the triggers for declaring any highway segment in need of improvement.

Below is a core list of the road conditions for which the software identifies deficiencies and the corresponding performance measure being utilized to identify the deficiencies:

- Pavement condition (IRI/PSI)
- Mobility condition (peak hour V/C ratio)
- Roadway Geometric Alignment Adequacy—to reflect roadway safety condition—(Horizontal & Vertical alignment adequacy ratings)

Potential improvement options are generated for each road section to eliminate these deficiencies. The improvement options to address deficiencies are generated in a somewhat hierarchical manner. First, the HERS-ST software identifies sections with pavement condition deficiencies. Then, only the sections that are identified to have pavement condition deficiency are screened for deficiencies in mobility condition and roadway alignment adequacy. Figure 2.2 provides a schematic of the process by which HERS-ST generates potential improvements for deficiencies in road sections.

Once deficiencies are identified for each road section, the HERS-ST software calculates a benefit-cost ratio for each improvement proposed for a road section. The ratio is calculated to prioritize which improvements get implemented in a budget-constrained context.

The future benefits resulting from an improvement consist of

- vehicle operating cost savings [due to implementation of a proposed pavement improvement]

TABLE 2.3
Initial (2009) and final (2029) VMT of the State Urban roads

	Interstates and Expressways	Other Arterials	Major Collectors	Total
Initial (2009) VMT of Indiana's State Urban Highway Network (in Millions)	10803	8762	40	19605
Final (2029) VMT of Indiana's State Urban Highway Network (in Millions)	15988	9831	45	25864

TABLE 2.4
Initial (2009) and Final (2029) VMT of the State Rural Arterials

	Interstates	Other Arterials	Total
Initial (2009) VMT of Indiana's State Urban Highway Network (in Millions)	6667	7818	14485
Final (2029) VMT of Indiana's State Urban Highway Network (in Millions)	7374	7896	15270

TABLE 2.5
Initial (2009) and final (2029) VMT of the Federal-Aid Urban roads

	Interstates and Expressways	Other Arterials	Major Collectors	Total
Initial (2009) VMT of Indiana's Federal-Aid Urban Network (in Millions)	10971	18233	6087	35291
Final (2029) VMT of Indiana's Federal-Aid Urban Network (in Millions)	16236	20457	6829	43522

TABLE 2.6
Initial pavement roughness condition of State-Owned Urban roads (total & broken down into three components)

	State-Owned Urban roads	Urban Interstates and Expressways	Other State-Owned Urban Arterials	State-Owned Urban Major Collectors
Percent road miles with IRI <95	45.5	51.4	43.9	26.0
Percent road miles with 95≤ IRI <120	22.1	28.0	20.4	0.0
Percent road miles with 120≤ IRI <145	14.9	7.7	17.0	30.7
Percent road miles with 145≤ IRI <170	8.3	5.4	8.9	39.3
Percent road miles with 170≤ IRI <195	3.2	0.9	3.9	4.0
Percent road miles with IRI ≥195	6.0	6.6	5.9	0.0

TABLE 2.7
Initial Pavement Roughness Condition of State-Owned Rural Arterials (total & broken down into two components)

	All State-Owned Rural Arterials	Rural Interstates	Other State-Owned Rural Arterials
Percent road miles with IRI <95	75.9	74.9	76.1
Percent road miles with 95≤ IRI <120	15.4	22.2	14.1
Percent road miles with 120≤ IRI <145	4.6	2.9	5.0
Percent road miles with 145≤ IRI <170	0.9	0.0	1.0
Percent road miles with 170≤ IRI <195	1.2	0.0	1.4
Percent road miles with IRI ≥195	2.0	0.0	2.4

TABLE 2.8
Initial Pavement Roughness Condition of Federal-Aid Urban roads (total & broken down alternatively into Arterials/Collectors OR State-Owned/Non State-Owned)

	Federal-Aid Urban roads	All Urban Arterials	All Urban Major Collectors	State-Owned Urban roads	Non-State-Owned Urban roads
Percent road miles with IRI <95	64.2	58.1	74.9	45.5	71.9
Percent road miles with 95≤ IRI <120	8.6	13.1	0.8	22.1	3.0
Percent road miles with 120≤ IRI <145	7.0	9.3	3.0	14.9	3.8
Percent road miles with 145≤ IRI <170	3.8	5.5	1.0	8.3	2.0
Percent road miles with 170≤ IRI <195	3.2	2.6	4.0	3.2	3.2
Percent road miles with IRI ≥195	13.2	11.4	16.3	6.0	16.1

TABLE 2.9
Initial peak-hour mobility condition of State-Owned Urban roads, by roadway miles (total & broken down into three components)

	State-Owned Urban roads	Urban Interstates and Expressways	Other State-Owned Urban Arterials	State-Owned Urban Major Collectors
Percent road miles with V/C <0.7	94.3	85.1	97.2	100.0
Percent road miles with 0.7≤ V/C <0.8	3.1	7.0	1.9	0.0
Percent road miles with V/C ≥0.8	2.6	7.9	0.9	0.0

TABLE 2.10
Initial peak-hour mobility condition of State-Owned Rural Arterials (total & broken down into two components), by roadway miles

	All State-Owned Rural Arterials	Rural Interstates	Other State-Owned Rural Arterials
Percent road miles with V/C <0.7	99.8	98.2	100.0
Percent road miles with 0.7≤ V/C <0.8	0.2	1.3	0.0
Percent road miles with V/C ≥0.8	0.0	0.5	0.0

TABLE 2.11
Initial peak-hour mobility condition of Federal-Aid Urban roads, by roadway miles (total & broken down alternatively into Arterials/Collectors OR State-Owned/Non State-Owned)

	Federal-Aid Urban roads	All Urban Arterials	All Urban Major Collectors	State-Owned Urban roads	Non State-Owned Urban roads
Percent road miles with V/C <0.7	84.9	88.6	78.6	94.3	81.0
Percent road miles with 0.7≤ V/C <0.8	3.2	3.4	2.8	3.1	3.3
Percent road miles with V/C ≥0.8	11.9	8.0	18.6	2.6	15.7

TABLE 2.12
Initial peak-hour mobility condition of State-Owned Urban roads, by VMT (total & broken down into three components)

	State-Owned Urban roads	Urban Interstates and Expressways	Other State-Owned Urban Arterials	State-Owned Urban Major Collectors
Percent of VMT traveling on roads experiencing V/C <0.7 during the peak hour	77.5	64.0	91.0	100.0
Percent of VMT traveling on roads experiencing 0.7≤ V/C <0.8 during the peak hour	10.5	15.7	5.8	0.0
Percent of VMT traveling on roads experiencing V/C ≥0.8 during the peak hour	12.0	20.3	3.2	0.0

TABLE 2.13
Initial peak-hour mobility condition of State-Owned Rural Arterials, by VMT (total & broken down into two components)

	All State-Owned Rural Arterials	Rural Interstates	Other State-Owned Rural Arterials
Percent of VMT traveling on roads experiencing V/C <0.7 during the peak hour	98.2	96.1	100.0
Percent of VMT traveling on roads experiencing 0.7≤ V/C <0.8 during the peak hour	1.2	2.6	0.0
Percent of VMT traveling on roads experiencing V/C ≥0.8 during the peak hour	0.6	1.3	0.0

TABLE 2.14
Initial peak-hour mobility condition of Federal-Aid Urban roads, by VMT (total & broken down alternatively into Arterials/Collectors OR State-Owned/Non State-Owned)

	Federal-Aid Urban roads	All Urban Arterials	All Urban Major Collectors	State-Owned Urban roads	Non State-Owned Urban roads
Percent of VMT traveling on roads experiencing V/C <0.7 during the peak hour	75.0	76.9	66.2	77.5	71.9
Percent of VMT traveling on roads experiencing 0.7≤ V/C <0.8 during the peak hour	7.5	8.3	3.1	10.5	3.7
Percent of VMT traveling on roads experiencing V/C ≥0.8 during the peak hour	17.5	14.8	30.7	12.0	24.4

TABLE 2.15
Horizontal alignment adequacy rating for a road segment (FHWA Office of Highway Policy Information 2005)

Code	Description
1	All curves meet appropriate design standards for the type of roadway. Reduction of curvature would be unnecessary even if reconstruction were required to meet other deficiencies (i.e., capacity, vertical alignment, etc.).
2	Although some curves are below appropriate design standards for new construction, all curves can be safely and comfortably negotiated at the prevailing speed limit on the section. The speed limit was not established by the design speed of curves.
3	Infrequent curves with design speeds less than the prevailing speed limit on the section. Infrequent curves may have reduced speed limits for safety purposes.
4	Several curves uncomfortable or unsafe when traveled at the prevailing speed limit on the section, or the speed limit on the section is severely restricted due to the design speed of curves.

TABLE 2.16
Vertical alignment adequacy rating for a road segment (FHWA Office of Highway Policy Information 2005)

Code	Description
1	All grades (rate and length) and vertical curves meet minimum design standards appropriate for the terrain. Reduction in rate or length of grade would be unnecessary even if reconstruction were required to meet other deficiencies (i.e., capacity, horizontal alignment, etc.).
2	Although some grades (rate and/or length) and vertical curves are below appropriate design standards for new construction, all grades and vertical curves provide sufficient sight distance for safe travel and do not substantially affect the speed of trucks.
3	Infrequent grades and vertical curves that impair sight distance or affect the speed of trucks (when truck climbing lanes are not provided).
4	Frequent grades and vertical curves that impair sight distance or severely affect the speed of trucks; truck climbing lanes are not provided.

TABLE 2.17
Horizontal alignment adequacy rating of State-Owned Urban roads (total & broken down into three components)

	State-Owned Urban roads	Urban Interstates and Expressways	Other State-Owned Urban Arterials	State-Owned Urban Major Collectors
Percent road miles with no information on horizontal alignment adequacy rating	71.9	70.5	73.4	0.0
Percent road miles with horizontal alignment adequacy rating of 1	26.9	29.5	25.1	96.0
Percent road miles with horizontal alignment adequacy rating of 2	0.5	0.0	0.7	0.0
Percent road miles with horizontal alignment adequacy rating of 3	0.3	0.0	0.4	0.0
Percent road miles with horizontal alignment adequacy rating of 4	0.4	0.0	0.4	4.0

TABLE 2.18
Vertical alignment adequacy rating of State-Owned Urban roads (total & broken down into three components)

	State-Owned Urban roads	Urban Interstates and Expressways	Other State-Owned Urban Arterials	State-Owned Urban Major Collectors
Percent road miles with no information on vertical alignment adequacy rating	71.9	70.5	73.4	0.0
Percent road miles with vertical alignment adequacy rating of 1	25.3	26.8	23.9	93.7
Percent road miles with vertical alignment adequacy rating of 2	2.1	2.7	1.9	6.3
Percent road miles with vertical alignment adequacy rating of 3	0.5	0.0	0.6	0.0
Percent road miles with vertical alignment adequacy rating of 4	0.2	0.0	0.2	0.0

TABLE 2.19
Horizontal alignment adequacy rating of State-Owned Rural Arterials (total & broken down into two components)

	All State-Owned Rural Arterials	Rural Interstates	Other State-Owned Rural Arterials
Percent road miles with horizontal alignment adequacy rating of 1	74.7	100.0	69.8
Percent road miles with horizontal alignment adequacy rating of 2	8.9	0.0	10.6
Percent road miles with horizontal alignment adequacy rating of 3	15.7	0.0	18.8
Percent road miles with horizontal alignment adequacy rating of 4	0.7	0.0	0.8

TABLE 2.20
Vertical alignment adequacy rating of State-Owned Rural Arterials (total & broken down into two components)

	All State-Owned Rural Arterials	Rural Interstates	Other State-Owned Rural Arterials
Percent road miles with vertical alignment adequacy rating of 1	58.4	86.1	53.0
Percent road miles with vertical alignment adequacy rating of 2	24.2	13.9	26.2
Percent road miles with vertical alignment adequacy rating of 3	12.1	0.0	14.4
Percent road miles with vertical alignment adequacy rating of 4	5.3	0.0	6.4

TABLE 2.21
Horizontal alignment adequacy rating of Federal-Aid Urban roads (total & broken down alternatively into Arterials/Collectors OR State-Owned/Non State-Owned)

	Federal-Aid Urban roads	All Urban Arterials	All Urban Major Collectors	State-Owned Urban roads	Non State-Owned Urban roads
Percent road miles with no information on horizontal alignment adequacy rating	90.5	86.8	100.0	71.9	98.2
Percent road miles with horizontal alignment adequacy rating of 1	8.2	12.2	0.0	26.9	0.5
Percent road miles with horizontal alignment adequacy rating of 2	0.9	0.6	0.0	0.5	1.1
Percent road miles with horizontal alignment adequacy rating of 3	0.2	0.2	0.0	0.3	0.1
Percent road miles with horizontal alignment adequacy rating of 4	0.2	0.2	0.0	0.4	0.1

TABLE 2.22
Vertical alignment adequacy rating of Federal-Aid Urban roads (total & broken down alternatively into Arterials/Collectors OR State-Owned/Non State-Owned)

	Federal-Aid Urban roads	All Urban Arterials	All Urban Major Collectors	State-Owned Urban roads	Non State-Owned Urban roads
Percent road miles with no information on vertical alignment adequacy	90.6	86.8	100.0	71.9	98.2
Percent road miles with vertical alignment adequacy rating of 1	7.9	11.8	0.0	25.3	0.7
Percent road miles with vertical alignment adequacy rating of 2	1.3	1.1	0.0	2.1	0.9
Percent road miles with vertical alignment adequacy rating of 3	0.2	0.2	0.0	0.5	0.2
Percent road miles with vertical alignment adequacy rating of 4	0.0	0.1	0.0	0.2	0.0

- user cost savings due to reductions in travel time [due to implementation of a proposed mobility condition improvement]
- fewer collisions [due to implementation of a geometric alignment correction]

The process shown in Figure 2.2 has influenced how the analysis for addressing pavement and mobility deficiencies has been conducted. Two different procedures were used to generate results for the pavement and mobility asset types, as shown in Figures 2.3 and 2.4, respectively. Figure 2.3 shows that for the pavement runs, the deficiency screening process was modified in order to identify deficiencies only in pavement condition. This was accomplished by modifying the mobility and geometric alignment adequacy standards so that none of the road sections are identified as having deficiency in mobility condition or geometric alignment adequacy.

Figure 2.4 shows that for the mobility runs, the deficiency screening process was modified in order to identify deficiencies in mobility condition. Figure 2.2 shows that HERS-ST first screens each road section for deficiency in pavement condition and then for deficiency in mobility and alignment adequacy. Therefore, the deficiency screening process was modified in order to allow all road sections to be identified as exhibiting pavement condition deficiency. This is a necessary step to ensure all road sections can get screened for mobility condition deficiency. The geometric alignment adequacy standards were set so that none of the road sections are identified as having deficiency in geometric alignment adequacy. The pavement improvement costs were set at zero so that proposed pavement improvements are implemented at no cost. This modification prevents the implementation of pavement improvements from affecting the budget-constraint that is assigned to implement mobility improvement.

No analysis was conducted to address safety condition deficiency as represented by the alignment adequacy ratings. There are several reasons for this, including the fact that for the State Urban road network and the Federal-Aid Urban road network, most of the horizontal and vertical alignment adequacy information is missing (See Tables 2.17, 2.18, 2.21, and 2.22). Additionally, HPMS data does not contain crash rate information and the process by which HERS-ST software estimates the influence of alignment correction (safety restorative action) on network-level roadway safety is flawed; the overall crash rate as well as fatality and severe injury rates are calculated for each functional class based purely upon the alignment adequacy measures and roadway geometry, without calibration to the currently observed metrics.

2.5 Relevant Data for Condition Modeling

HERS-ST uses the equations contained in the 1993 AASHTO Guide for Design of Pavement Structures as pavement condition deterioration models. The data items that are used by HERS-ST to predict future pavement condition for a pavement section are Surface Type, [initial] PSI/equivalent IRI, Structural Number

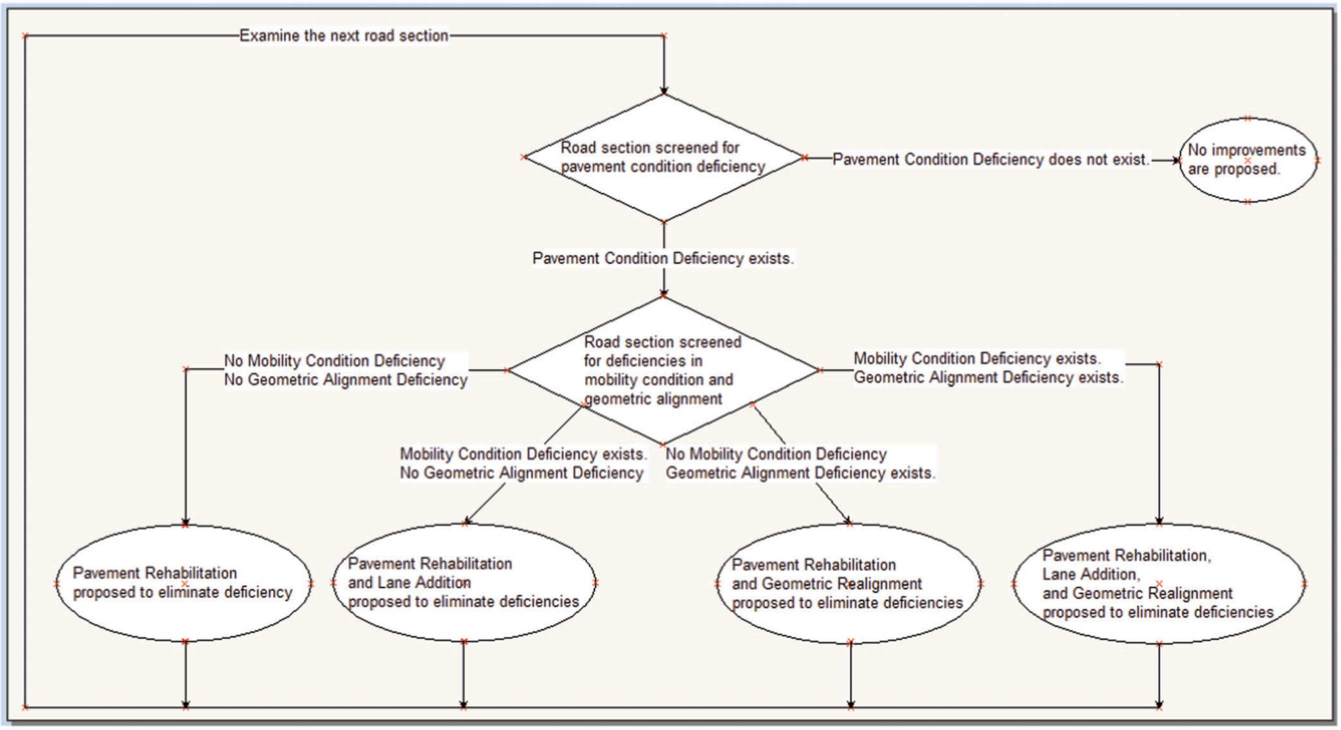


Figure 2.2 HERS-ST process for screening each road section for deficiencies in pavement condition, mobility condition, and geometric alignment adequacy and proposing potential restorative improvements.

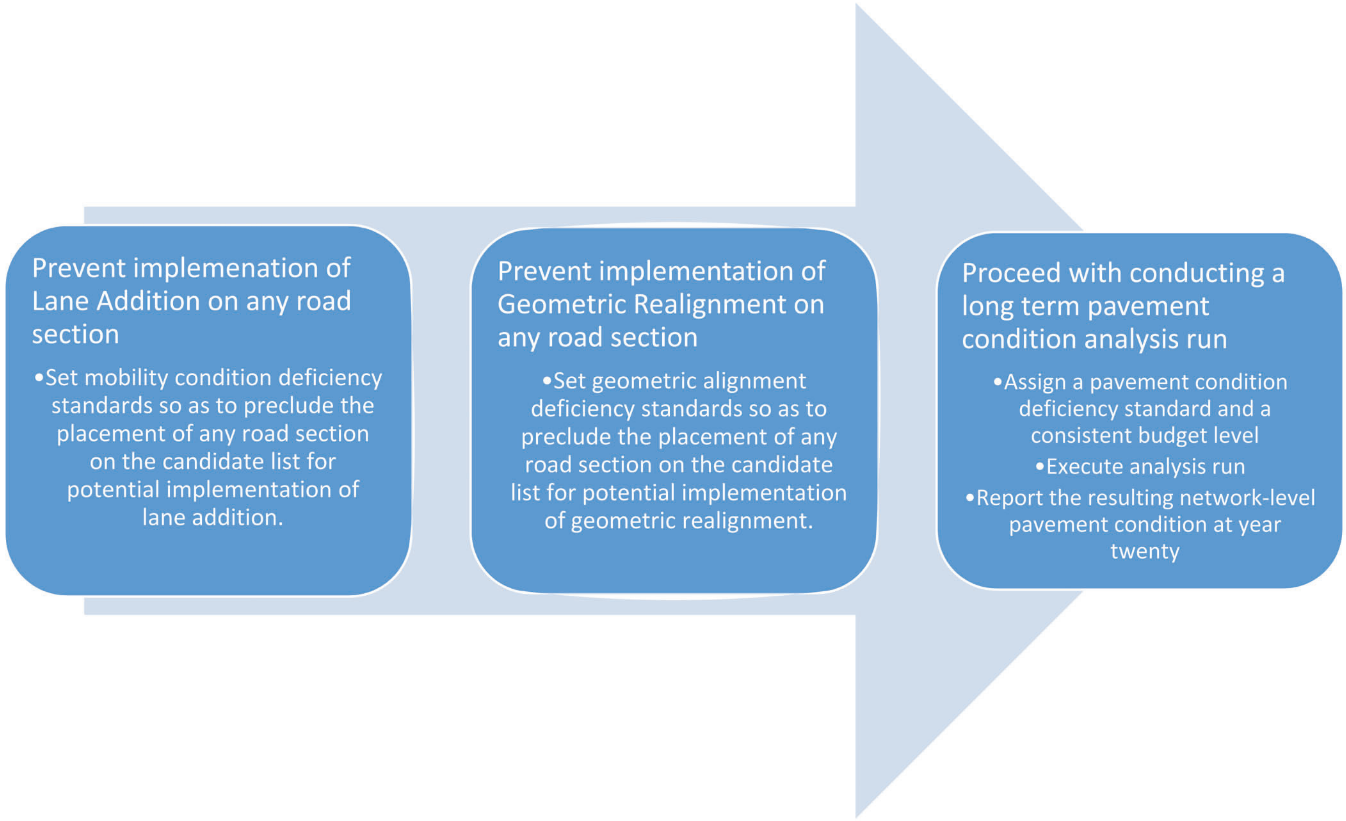


Figure 2.3 Modifications made to the HERS-ST deficiency screening process to ensure that only pavement improvements are proposed.

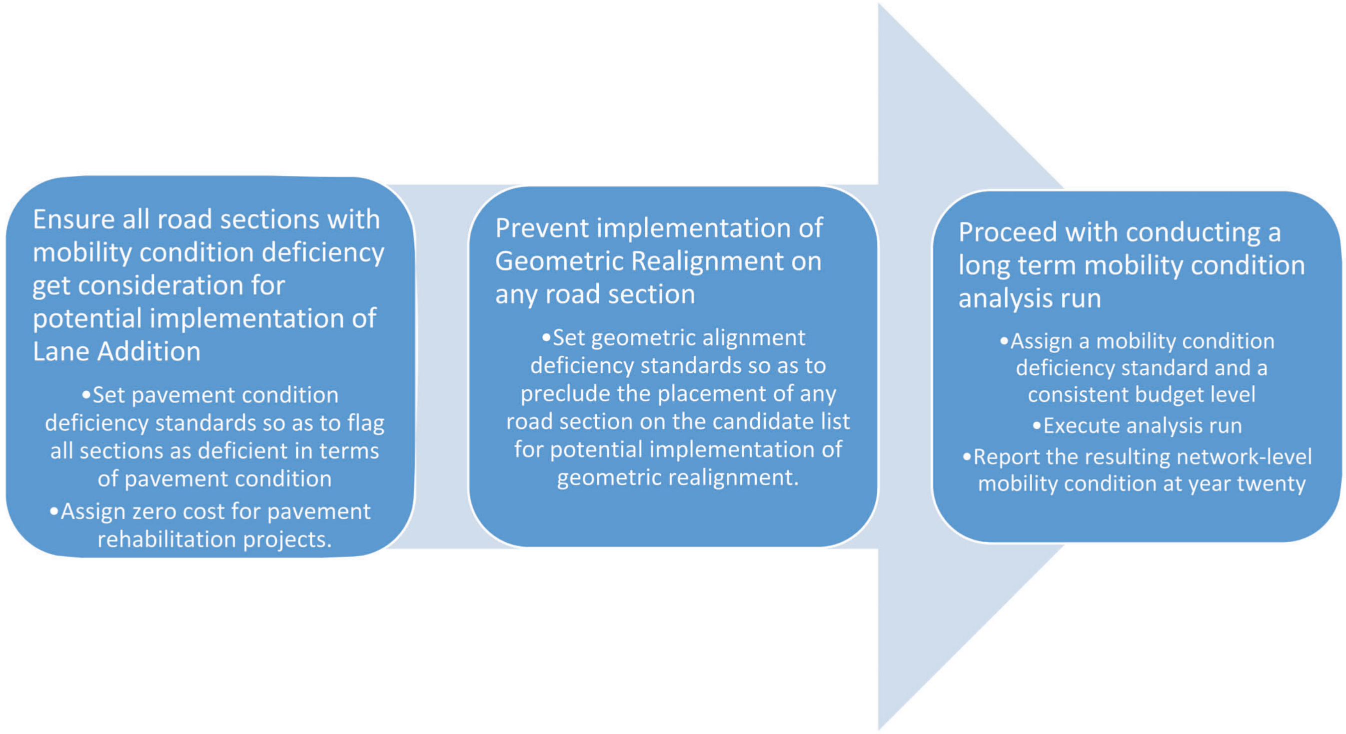


Figure 2.4 Modifications made to the HERS-ST deficiency screening process to ensure improvements are proposed for mobility-deficient sections.

(SN) for flexible pavements, depth of slab (D) for concrete pavements, FHWA Climate Classification, Average Annual Daily Traffic (AADT), and Average percentages of Single-Unit and Combination Trucks. The effect of the climate is calculated and applied as the minimum rate of deterioration for a pavement section.

For the Mobility Condition Modeling, HERS-ST uses the following data items: Average Annual Daily Traffic (AADT), Number of Through Lanes, K Factor, Directional Factor, Number of Peak Lanes, and Peak percentages of Single-Unit and Combination Trucks. The mobility condition runs were conducted with the assumption of linear growth in traffic between the Years 2009 and 2029.

For more information, the HERS-ST Technical Report (FHWA Office of Asset Management, 2005) can be consulted.

2.6 Results Compilation

The results from a HERS-ST run produces three sets of files for the end of each Funding Period (5 years) within an Analysis Period (20 years): Section Condition, System Condition, and Improvement Statistics. The Section Condition files specify the condition of individual road segments whether or not any improvements are implemented on them. The System Condition files contain information such as the VMT on the roads and the network-level pavement or mobility condition. The Improvement Statistics files give information about the types of improvement projects made to the network and their costs. The results are broken down by functional class, as shown in Tables 2.1 and 2.2. The results can be exported into Excel CSV files.

HERS-ST does not currently contain an automatic method for changing the breakdown of the results from the functional class one into an alternative one, such as the State-Owned vs. Non-State-Owned breakdown for a Federal-Aid road network. Such a breakdown can be accomplished manually by opening a Section Condition file and compiling the results from that file by choosing the roads under State Ownership.

For more information, the HERS-ST User Guide Document (FHWA Office of Asset Management, 2009) can be consulted.

3. PAVEMENT ASSET ANALYSIS RESULTS

3.1 Introduction

The purpose of this analysis is to provide a projection of the long-term consequences on a network's pavement condition of changing pavement rehabilitation treatment triggers and varying the budget available for treatment. A trigger value (or deficiency standard) is the pavement rating at which an appropriate treatment should be undertaken, so that the pavement will perform at a satisfactory level for a prescribed number of years. If the deficiency standard is set high, this means that a treatment is triggered earlier, or at a better condition level. The consequence is a better network condition, but this may be achieved at a higher cost. Conversely, a Low Deficiency Standard means that treatments are triggered later on at worse condition levels. Waiting longer to treat pavement sections may seem like a plausible strategy to reduce expended agency cost, but adopting this strategy in the long term can result in widespread poor pavement conditions in the network, which is expensive to reverse. The analyses in this project investigate the tradeoffs and trends involved in changing the trigger value at various budget levels.

The research team used the Highway Economic Requirement System (HERS-ST) software to observe how the trigger levels defined for different pavement rehabilitation treatments affect the pavement conditions for the State-Owned network and the Federal-Aid Highway network (excluding Rural Major Collectors). HERS-ST is an asset management tool that enables highway agencies to approximate their funding needs for long-term preservation of the Federal-Aid roadway system, or its subset, the State highway system. It should be noted that HPMS input to HERS does not contain two road classifications that are outside of the Federal-Aid Highway system; these roads are rural minor collectors and local roads.

Indiana's 2009 Highway Performance Monitoring System (HPMS) sample section data was used as the input. The HERS-ST software takes HPMS data as input and, based upon certain data items, identifies deficiencies in roadways assets:

- pavement assets (Pavement Serviceability Rating)
- mobility condition (peak hour V/C ratio), and
- geometric alignment (horizontal alignment adequacy and vertical alignment adequacy).

The HERS-ST software provides the flexibility of changing the deficiency standards. Changing the deficiency (trigger) levels in HERS-ST influences the network condition. Once deficient sections are identified, the HERS-ST software prioritizes potential improvements using a benefit-cost ratio. The future benefits resulting from an improvement consist of

- user cost savings due to reductions in travel time,
- vehicle operating cost savings, and
- fewer collisions.

After implementation of the improvements, HERS-ST recalculates road section conditions and aggregates them to reflect a system's condition in terms of percent of sections exceeding a certain performance threshold.

In the case of pavement assets, the use of the HPMS data is an advantage because the dataset contains spatial coverage of both the State and the Federal-Aid system. Additionally, it provides a number of both pavement and traffic data items necessary to calculate pavement deterioration such as IRI, effective Structural Number for Asphalt Pavements/Depth of Slab for Concrete pavements, Annual Average Daily Traffic, Traffic Directional Factor, and Percent Average Daily Combination Trucks: four-or-fewer axles, single-trailer trucks through seven or-more axle, multi-trailer trucks (FHWA vehicle classes 8–13).

Because the network's condition improves the most by implementing more improvements, it is expected that identifying a greater number of deficient sections (raising the deficiency standard) and increasing the funding will result in a better network condition. This expectation was validated by the forthcoming results of the analysis.

3.2 Use of HERS-ST Software to Generate Pavement Analysis Results

Three pavement rehabilitation trigger sets (deficiency standards) were defined to represent the conditions at which pavement rehabilitation treatments could be implemented. Tables 3.1–3.3 show the set of pavement conditions that make up the "Low Condition Level", "Medium Condition Level", and "High Condition Level" trigger sets for placing pavement sections on the candidate list to receive "heavy" or "moderate" strength pavement rehabilitation.

The term "heavy rehabilitation" is meant to represent rehabilitation treatments of a strength equivalent to a HMA Structural Overlay (up to 8 inch overlay), for example.

The term "moderate rehabilitation" and is meant to represent rehabilitation treatments of a strength equivalent to a HMA Functional Overlay (2–4 inch overlay).

The "Medium Condition Level" trigger set was developed as an approximation to current (as of August 2012) INDOT policy in identifying sections eligible for receiving pavement rehabilitation (shown in Table 3.4). Table 3.4 contains both roughness and rut depth metrics to trigger pavement rehabilitation. However, the rut depth metric might not be a decisive factor in triggering pavement rehabilitation because in 2009, only 1% of Indiana state highway pavement sections (110 miles) had a rut depth greater than 0.35 inches.

The "Low" trigger set was developed to demonstrate the impact on pavement network condition of reducing the pavement rehabilitation candidate list to include pavement sections in worse condition (relative to the "Medium" trigger set). Conversely, the "High" trigger set was developed to demonstrate the impact on pavement network condition of expanding the pavement rehabilitation candidate list to include pavement sections in better condition (relative to the "Medium" trigger set). Note that the trigger values vary by road classification as a way to indicate that a higher priority may be placed on treating deficient pavements on roadways with a higher functional class.

Improvement Cost and Post-treatment Performance Information

The "heavy" and "moderate" pavement rehabilitation costs, in units of thousands of 2008 constant dollars per lane mile, were set as shown in Table 3.5, in the left and right columns, respectively.

These costs were developed based on input from Mr. Allen Davidson, who operates the pavement asset management module of the dTIMS software (see Table 3.4).

The cost differential contained for a certain treatment implemented in different locations is based upon the cost differential that existed for the default pavement treatment cost values contained in HERS.

Cost of treatments implemented on rural roads varies by terrain, whereas costs implemented on urban roads vary by the type of urbanized area as defined by the population:

- Small urban—population 5,000–49,999
- Small urbanized—population 50,000–199,999
- Large urbanized—population 200,000 or more

Table 3.6 shows the post-treatment performance for pavements that have undergone rehabilitation treatments (Irfan et al., 2009).

The three pavement deficiency standards mentioned earlier were applied to three networks, the State Urban

TABLE 3.1
"Low Condition Level" Pavement Rehabilitation trigger set (Low Deficiency Standard)

Road Classification	"Heavy" Rehabilitation (PSI/equivalent IRI)		"Moderate" Rehabilitation (PSI/equivalent IRI)	
Rural				
Interstate	2.1	166	2.7	138
Principal Arterial AADT>6000	2.1	166	2.7	138
Principal Arterial AADT<6000	2.1	166	2.5	146
Minor Arterial	1.7	191	2.3	156
Major Collector	1.7	191	2.1	166
Urban				
Interstate	2.1	166	2.7	138
Expressway/Freeway	2.1	166	2.7	138
Principal Arterial	2.1	166	2.5	146
Minor Arterial	1.7	191	2.3	156
Collectors	1.7	191	2.1	166

TABLE 3.2

“Medium Condition Level” Pavement Rehabilitation trigger set (Medium Deficiency Standard)

Road Classification	“Heavy” Rehabilitation (PSI/equivalent IRI)		“Moderate” Rehabilitation (PSI/equivalent IRI)	
Rural				
Interstate	2.4	151	3	126
Principal Arterial AADT>6000	2.4	151	3	126
Principal Arterial AADT<6000	2.4	151	2.8	133
Minor Arterial	2	172	2.6	142
Major Collector	2	172	2.4	151
Urban				
Interstate	2.4	151	3	126
Expressway/Freeway	2.4	151	3	126
Principal Arterial	2.4	151	2.8	133
Minor Arterial	2	172	2.6	142
Collectors	2	172	2.4	151

TABLE 3.3

“High Condition Level” Pavement Rehabilitation trigger set (High Deficiency Standard)

Road Classification	“Heavy” Rehabilitation (PSR/IRI)		“Moderate” Rehabilitation (PSR/IRI)	
Rural				
Interstate	2.7	138	3.3	115
Principal Arterial AADT>6000	2.7	138	3.3	115
Principal Arterial AADT<6000	2.7	138	3.1	122
Minor Arterial	2.3	156	2.9	129
Major Collector	2.3	156	2.7	138
Urban				
Interstate	2.7	138	3.3	115
Expressway/Freeway	2.7	138	3.3	115
Principal Arterial	2.7	138	3.1	122
Minor Arterial	2.3	156	2.9	129
Collectors	2.3	156	2.7	138

TABLE 3.4

Current (as of August 2012) INDOT policy for identifying sections eligible for heavy and moderate pavement rehabilitation treatment

Description	Trigger	Effect on Age	Cost ($\$/\text{yd}^2$)
Concrete Pavement Restoration	For concrete pavements: in any of index years 8 through 12 if average IRI is 130 or more. Not an option for flexible pavements.	Resets to 0	\$5.00
HMA Overlay (2–4 inches)	For flexible pavements: in any of years 8 through 12 if IRI is less than 130 and rut depth is less than 0.375″.	Resets to 0	\$6.00
HMA Mill & Fill	For flexible pavements: if IRI is between 110 and 150, or if rut depth is between 0.375″ and 0.625″.	Resets to 0	\$8.50
Heavy Rehabilitation—e.g., HMA Overlay (up to 8 inches) OR PCCP overlay	If IRI is between 140 and 170, or if rut depth is between 0.5″ and 0.75″.	Resets to 0	\$20.00

TABLE 3.5
Cost of pavement "Heavy" and "Moderate" strength rehabilitation treatments (thousands of 2008 constant dollars per lane mile)

	Functional classification	Category of Rural/Urban area	Cost of Heavy Rehabilitation (thousands of 2008 constant dollars per lane mile)	Cost of Moderate Rehabilitation (thousands of 2008 constant dollars per lane mile)
Rural	Interstates	Flat	200	100
		Rolling	215	105
		Mountainous	315	160
	Principal Arterials	Flat	160	80
		Rolling	180	90
		Mountainous	255	125
	Minor Arterials	Flat	145	70
		Rolling	155	75
		Mountainous	210	105
Urban	Interstates/Expressways	Small Urban	235	120
		Small Urbanized	280	140
		Large Urbanized	470	235
	Principal Arterials	Small Urban	200	100
		Small Urbanized	235	120
		Large Urbanized	295	150
	Arterials/Collectors	Small Urban	145	75
		Small Urbanized	165	85
		Large Urbanized	205	100

roadway network, State Rural Arterial roadway network (State-Owned Rural network, excluding Major Collectors), and the Federal-Aid Urban roadway network.

The results starting at Figure 3.1 demonstrate the influence of changing the pavement deficiency standards and the funding on the percentage of roadway miles of a certain network within each IRI condition category. The points on the graphs represent the network roadway condition as a result of 20 years of applying each deficiency standard and each five-year funding level.

3.3 Pavement Analysis Results for the State-Owned Urban roadway network

3.3.1 Pavement Roughness Condition of State-Owned Urban Roadways in 2029 due to Application of the Low Deficiency Standard for Triggering Pavement Rehabilitation During the 2009–2029 Period

Table 3.7 shows the pavement roughness condition for the State-Owned Urban roadway network, as well as for its primary components, the Urban Interstate and Expressways and the Other State-Owned Urban Arterials. The

TABLE 3.6
Post-treatment pavement condition

	Pavement condition (PSR)
Heavy Rehabilitation post-treatment condition	4
Moderate Rehabilitation performance jump	0.9
Moderate Rehabilitation maximum post-treatment condition	3.8

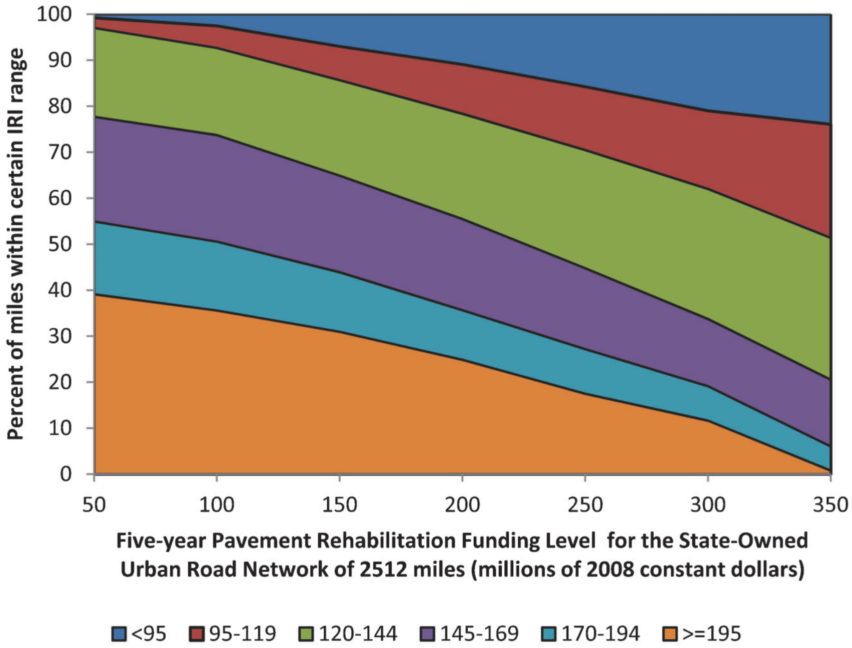


Figure 3.1 Pavement roughness of State Urban roads in 2029 under the Low Deficiency Standard for triggering pavement rehabilitation.

pavement roughness condition thresholds were reported as IRI<120 and IRI≥170 because, according to the FHWA, pavements with IRI<120 can be considered to be in good roughness condition, and pavements of IRI≥170 can be considered to be in poor roughness condition.

In plots like Figure 3.1, the pavements with the best IRI values are in the top band and the pavement with the worst IRI are in the lowest band.

Applying the Low Deficiency Standard for triggering pavement rehabilitation treatment on the State-Owned Urban roadway network results in:

- Notable increases in the percent of State Urban roadway miles within the condition categories of IRI<95 and 95<IRI<119.
- Corresponding decreases in the percent of roadway miles with IRI ≥170 (from 54.9% to 6.0%).
- For all funding levels, the pavement roughness condition for Urban Interstates and Expressways improving to a much greater extent than the overall State Urban network's pavement roughness condition with increased funding, as seen in Figure 3.2.
- As the funding increases, the pavement roughness condition of the Other State Urban Arterials subset improving significantly (Columns 5 and 6), but not as much as the improvement that the Urban Interstate and Expressway subset exhibits (Columns 3 and 4).
- At the consistent five-year funding level of $350 million, the percent of State Urban road miles with pavement roughness of IRI ≥170 dropping below 10%, as seen in Figure 3.1 and Table 3.7 Column 2.

TABLE 3.7
Pavement Roughness of State-Owned Urban roads in 2029 with different funding levels under the Low Deficiency Standard for triggering pavement rehabilitation during the 2009–2029 period

Five-year Pavement Rehabilitation Funding Level for the State-Owned Urban System (millions of 2008 constant dollars)	(1) Percent of State-Owned Urban roadway miles with IRI <120	(2) Percent of State-Owned Urban roadway miles with IRI ≥170	(3) Percent of Urban Interstate and Expressway miles with IRI <120	(4) Percent of Urban Interstate and Expressway miles with IRI ≥170	(5) Percent of Other State-Owned Urban Arterial roadway miles with IRI <120	(6) Percent of Other State-Owned Urban Arterial roadway miles with IRI ≥170
50	3.0	54.9	7.6	54.4	1.5	54.5
100	7.3	50.6	24.6	37.4	1.8	54.2
150	14.4	43.9	41.7	21.1	5.6	50.6
200	21.6	35.7	53.1	10.8	11.7	42.9
250	29.5	27.2	65.1	7.8	18.3	32.5
300	38.0	19.1	73.3	4.9	27.0	23.1
350	48.6	6.0	78.5	0.2	39.5	7.9

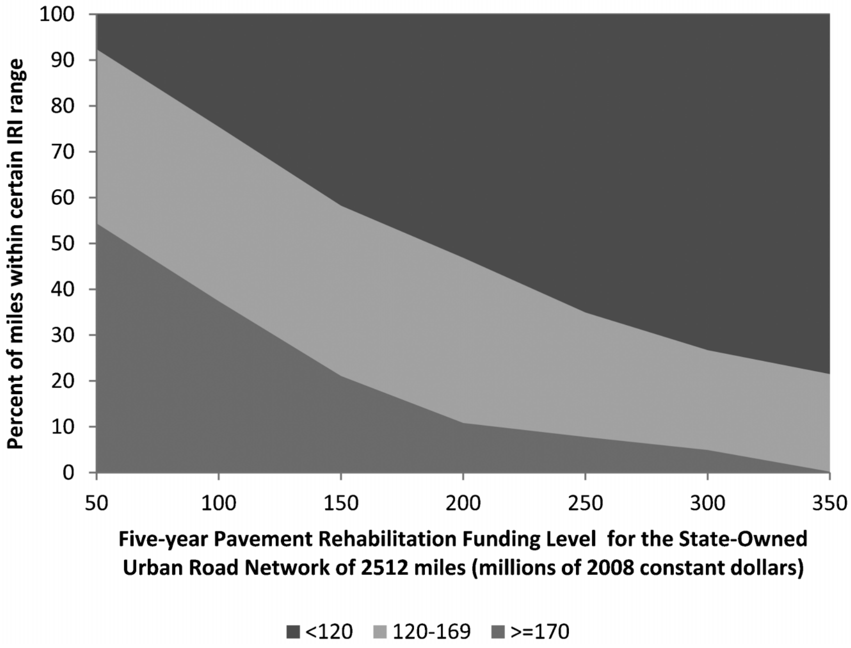


Figure 3.2 Pavement roughness of Urban Interstates and Expressways in 2029 under the Low Deficiency Standard for triggering pavement rehabilitation.

3.3.2 Pavement Roughness Condition of State-Owned Urban Roadways in 2029 due to Application of the Medium Deficiency Standard for Triggering Pavement Rehabilitation During the 2009–2029 Period

Figures 3.3 and 3.4 show that applying the Medium Deficiency Standard for triggering pavement rehabilitation treatment on the State-Owned Urban roadway network results in:

- Great increases in the percent of State Urban roadway miles within the condition categories of IRI <95 and 95< IRI <119.
- Corresponding decreases in the percent of roadway miles with IRI ≥170, from 39.6% to 0.7%.
- At a five-year funding level of $150 million and beyond, the pavement roughness condition for the Urban Interstate and Expressway subset (Columns 3 and 4) improving to a greater extent than the overall network's

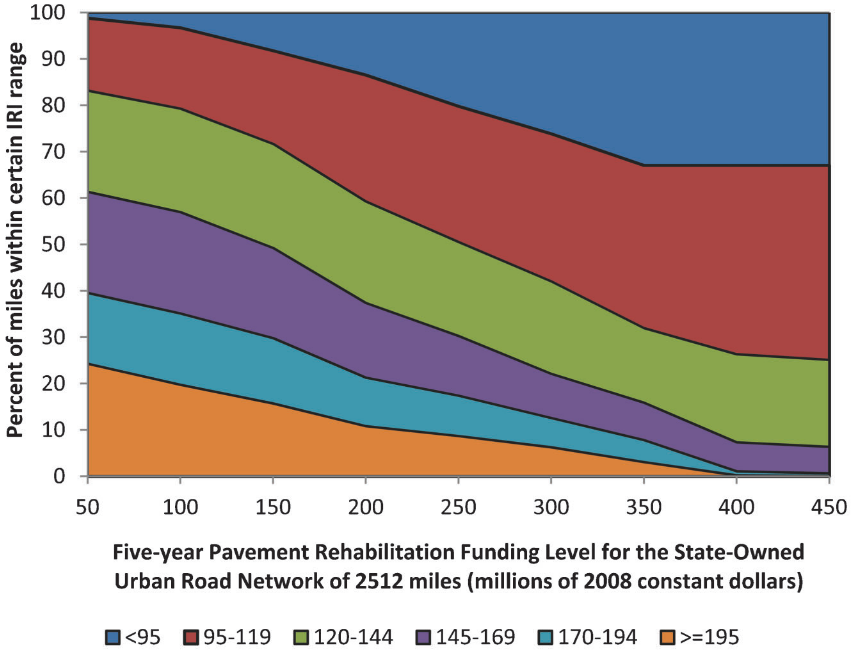


Figure 3.3 Pavement roughness of State Urban roads in 2029 under the Medium Deficiency Standard for triggering pavement rehabilitation.

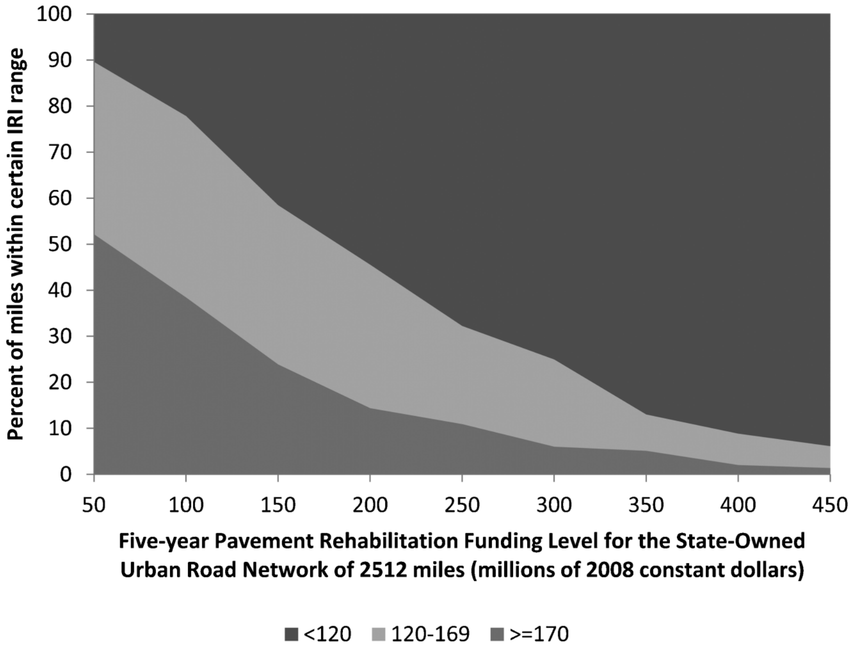


Figure 3.4 Pavement roughness of Urban Interstates and Expressways in 2029 with Medium Deficiency Standard for triggering pavement rehabilitation.

pavement roughness condition with increased funding (Columns 1 and 2) as shown by Figure 3.4 and Table 3.8.

- As with the Low Deficiency Standard, the consistent five-year funding level of $350 million dropping the percent of State Urban road miles with pavement roughness of IRI ≥170 below 10% (Table 3.8, Column 2).
- At the five-year funding level of $350 million, a greater percentage of State Urban road miles with pavement roughness of IRI <120 than with the Low Deficiency Standard (68.0% vs. 48.6%), as Table 3.8 shows.
- Beyond the five-year funding level of $400 million, no 2further improvement in the pavement condition for the State Urban road network.

3.3.3 Pavement Roughness Condition of State-Owned Urban Roadways in 2029 due to Application of the High Deficiency Standard for Triggering Pavement Rehabilitation During the 2009–2029 Period

Figures 3.5 and 3.6 show that applying the High Deficiency Standard for triggering pavement rehabilitation treatment on the State-Owned Urban roadway network results in:

- Dramatic increases in the percent of State Urban roadway miles within the condition categories of IRI <95 and 95< IRI <119.

TABLE 3.8
Pavement Roughness of State-Owned Urban roads in 2029 with different funding levels under the Medium Deficiency Standard for triggering pavement rehabilitation during the 2009–2029 period

Five-year Pavement Rehabilitation Funding Level for the State-Owned Urban System (millions of 2008 constant dollars)	(1) Percent of State-Owned Urban roadway miles with IRI <120	(2) Percent of State-Owned Urban roadway miles with IRI ≥170	(3) Percent of Urban Interstate and Expressway miles with IRI <120	(4) Percent of Urban Interstate and Expressway miles with IRI ≥170	(5) Percent of Other State-Owned Urban Arterial roadway miles with IRI <120	(6) Percent of Other State-Owned Urban Arterial roadway miles with IRI ≥170
50	16.8	39.6	10.4	52.2	19.2	34.7
100	20.7	35.1	22.1	38.4	20.5	33.2
150	28.3	29.8	41.5	23.9	24.4	30.9
200	40.7	21.3	54.4	14.4	36.8	22.5
250	49.5	17.4	67.7	10.9	44.2	18.4
300	57.9	12.6	75.0	6.0	53.2	14.1
350	68.0	7.8	87.0	5.1	62.8	7.5
400	73.7	1.1	91.1	2.0	69.0	0.7
450	74.9	0.7	93.9	1.4	69.7	0.4

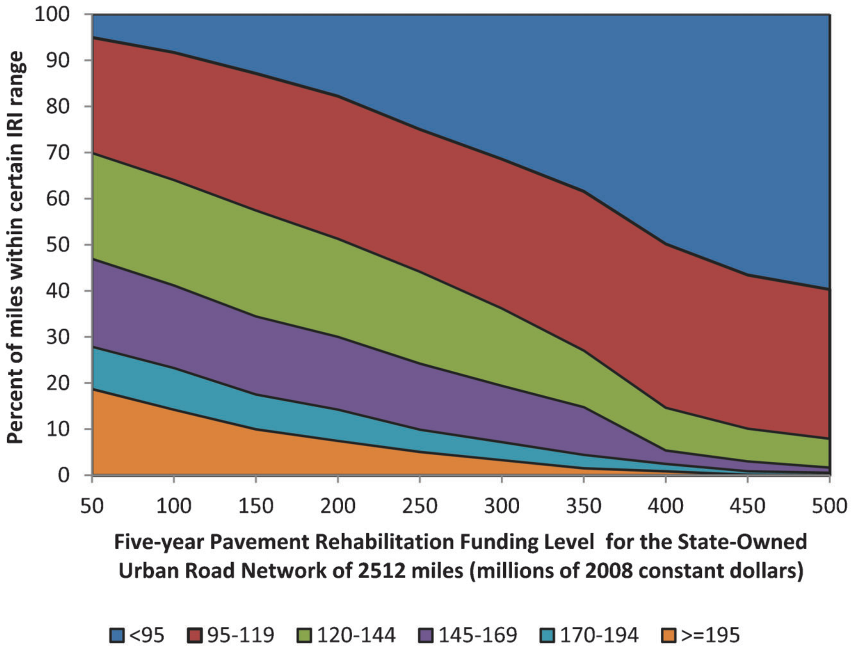


Figure 3.5 Pavement roughness of State Urban roads in 2029 with High Deficiency Standard for triggering pavement rehabilitation.

- Corresponding decreases in the percent of roadway miles with IRI ≥170 (from 27.9% to 0.6%).
- When the five-year funding level is $200 million or more, improvement in the pavement roughness condition for Urban Interstates and Expressways (Table 3.9 Columns 3 and 4) to a similar extent to the overall network's pavement roughness condition (Columns 1 and 2).
- At a five-year funding of $250 million, the percent of State Urban road miles with pavement roughness of IRI ≥170 dropping below 10% (Table 3.9, Column 2).
- Beyond the five-year funding level of $400 million, no further improvement in the pavement condition (Figure 3.5) for the State Urban road network.

Important Analysis Observations:

- At the lowest five-year funding level of $50 million and beyond, Tables 3.7–3.9 show that the deficiency standard being used to trigger pavement rehabilitation has a great impact on the network-level roughness

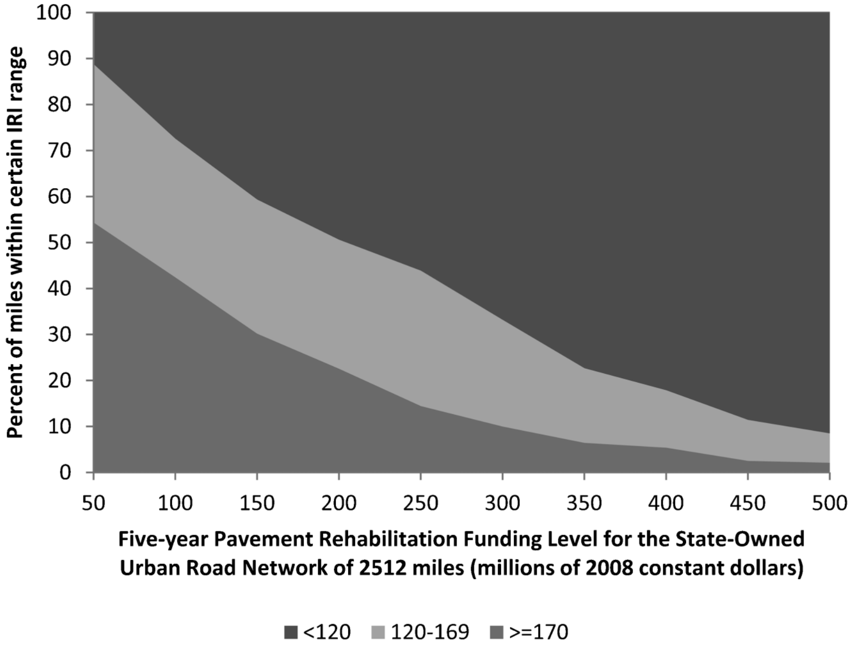


Figure 3.6 Pavement roughness of Urban Interstates and Expressways in 2029 with High Deficiency Standard for triggering pavement rehabilitation.

TABLE 3.9
Pavement Roughness of State-Owned Urban roads in 2029 with different funding levels under the High Deficiency Standard for triggering pavement rehabilitation during the 2009–2029 period

Five-year Pavement Rehabilitation Funding Level for the State-Owned Urban System (millions of 2008 constant dollars)	(1) Percent of State-Owned Urban roadway miles with IRI <120	(2) Percent of State-Owned Urban roadway miles with IRI ≥170	(3) Percent of Urban Interstate and Expressway miles with IRI <120	(4) Percent of Urban Interstate and Expressway miles with IRI ≥170	(5) Percent of Other State-Owned Urban Arterial roadway miles with IRI <120	(6) Percent of Other State-Owned Urban Arterial roadway miles with IRI ≥170
50	30.1	27.9	11.2	54.4	36.7	18.3
100	36.0	23.3	27.4	42.4	39.3	16.0
150	42.6	17.5	40.6	30.2	43.8	12.3
200	48.7	14.2	49.4	22.6	49.2	10.4
250	55.8	9.9	56.1	14.5	56.5	7.3
300	63.8	7.2	66.8	10.0	63.7	5.1
350	72.9	4.4	77.3	6.4	72.1	3.0
400	85.3	2.5	82.1	5.4	86.3	1.6
450	89.9	0.9	88.5	2.5	90.3	0.4
500	92.1	0.6	91.5	2.1	92.3	0.1

condition of the State Urban road network, especially on the non-Interstate and Expressway component of the network.

- The higher the trigger standard, the higher the percentage of State Urban miles in the IRI <120 pavement roughness category and the lower the percentage of miles in the IRI ≥170 category.
- As the funding level increases, the deficiency standard being applied to trigger pavement rehabilitation remains a significant factor in increasing the percent of State Urban road miles with smooth pavement (IRI <120) but progressively becomes a less relevant factor in decreasing the percent of road miles with rough pavement (IRI ≥170).

3.3.4 Summary of the Performance of the Pavement Rehabilitation Trigger Policies (Deficiency Standards) in Improving the Roughness Condition of State-Owned Urban Roads

To quantify the relative effects of the pavement rehabilitation trigger policy (deficiency standard) and the funding, ANCOVA analyses were conducted for two outcome variables: the percent of roadway miles in good roughness condition and in poor roughness condition.

- An ANCOVA analysis is a combination of ANOVA and regression, and it is part of the General Linear Model family.
- ANCOVA analysis reveals whether the relationship between the dependent variable, in this case the network-level pavement roughness condition outcome, and the quantitative covariate independent variable, in this case the five-year funding level for pavement rehabilitation, is linear and the slope is the same regardless of the level of the qualitative independent variable, which is the rehabilitation trigger policy.
- None of the models were developed to fit a situation with zero pavement rehabilitation funding over twenty years, because this is an entirely unreasonable situation.

The ANCOVA analysis for the outcome variable Percent of State-Owned Urban roadway miles in good roughness condition is shown in Table 3.10 and illustrated in Figure 3.7. This analysis result demonstrates that:

- Whatever pavement rehabilitation treatment trigger policy is enacted, the effect of increased funding has a constant magnitude in increasing the percent of State Urban roadway miles in good roughness condition (IRI <120). The effects of the trigger policy variable and the funding variable are independent of each other.

TABLE 3.10
ANCOVA Results for the outcome variable of percent of State-Owned Urban roadway miles in good roughness condition (IRI <120 in/mile) in 2029

	Variable description	Coefficient	Standard error	T-statistic	P-value
Constant	N/A	9.241	N/A	N/A	N/A
Covariant effect	Five-year Pavement Rehabilitation Funding Level (millions of 2008 constant dollars)	0.154	0.004	36.77	<0.001
Treatment Trigger Policy effect (Deficiency Standard)	Low Condition Level Trigger	−16.915	1.397	−12.11	<0.001
	Medium Condition Level Trigger		0 (Control)		
	High Condition Level Trigger	10.027	1.264	7.93	<0.001

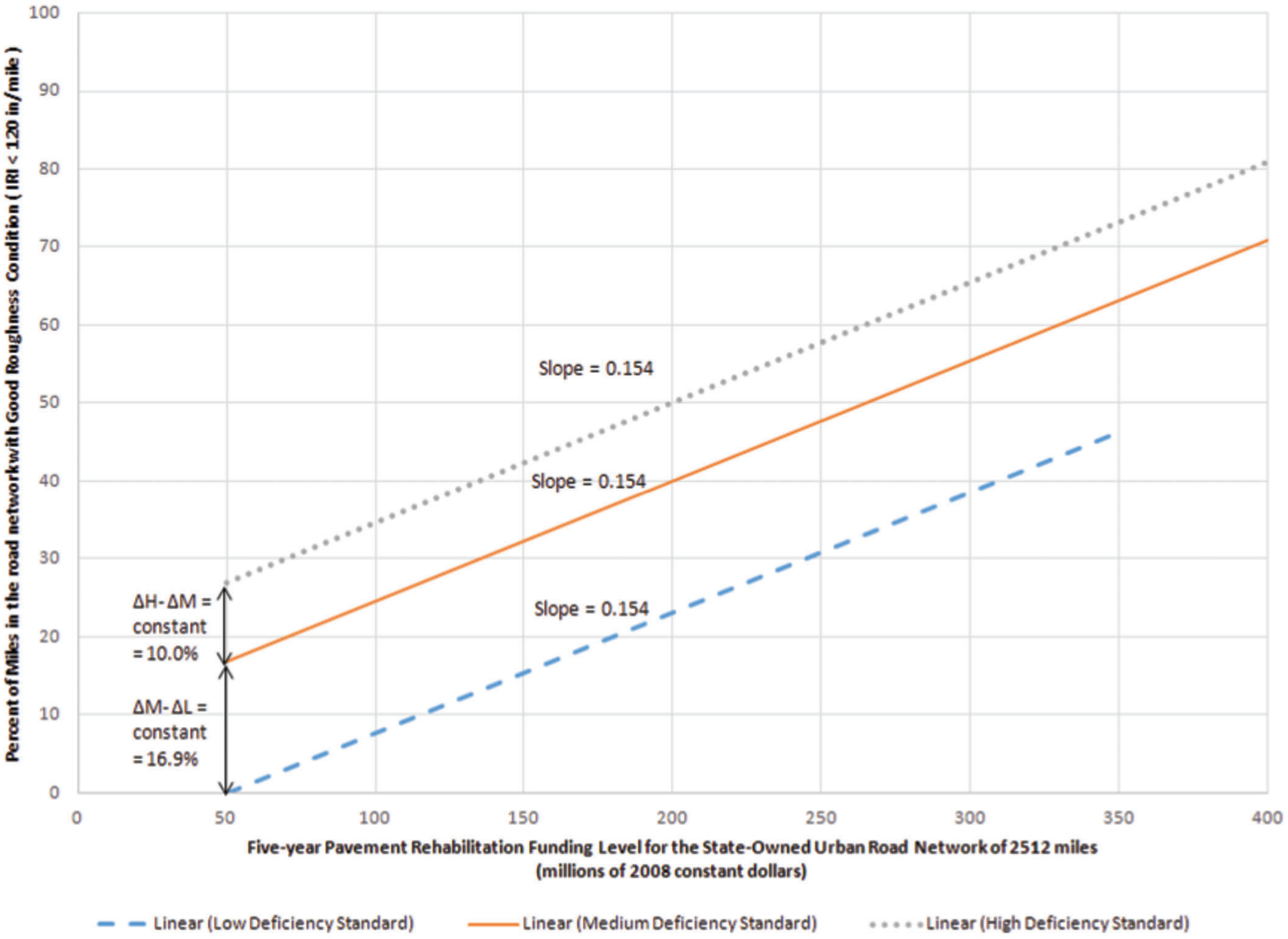


Figure 3.7 ANCOVA results for the outcome variable of percent of State-Owned Urban roadway miles in good roughness condition (IRI <120 in/mile) in 2029.

- Each increase of $10 million in the five-year pavement rehabilitation funding level causes an estimated increase of 1.5% in the number of State Urban road miles in good roughness condition in 2029.
- For all funding amounts, a change from the Medium Level to the Low Level policy would result in 16.9% fewer State Urban roadway miles in good condition.
- For all funding amounts, a change from the Medium Level to the High Level policy would result in 10.0% more State Urban roadway miles in good condition.

The ANCOVA analysis for the outcome variable of percent of State-Owned Urban roadway miles in poor roughness condition is shown in Table 3.11 and illustrated in Figure 3.8. This analysis shows that:

- There is a statistically significant interaction between the pavement rehabilitation funding and the choice of treatment trigger policy being implemented. As the five-year funding level is increased, the policy being applied to trigger pavement rehabilitation seems to become a progressively less relevant factor in decreasing the percent of State Urban road miles with rough pavement (IRI ≥170).
- If the Low Level trigger policy is implemented, each increase of $10 million in the five-year funding level causes an estimated decrease of 1.6% in the number of State Urban road miles in poor roughness condition.
- If the Medium Level trigger policy is implemented, each increase of $10 million in the five-year funding level causes an estimated decrease of 1.0% in the number of State Urban road miles in poor roughness condition.
- If the High Level trigger policy is implemented, each increase of $10 million in the five-year funding level causes an estimated decrease of 0.6% in the number of State Urban road miles in poor roughness condition.
- At the lowest five-year funding level of $50 million, a change from the Medium Level to the Low Level policy would result in 19.1% more State Urban roadway miles in poor condition, and
- A change from the Medium Level to the High Level policy would result in 14.3% fewer State Urban roadway miles in poor condition.

TABLE 3.11

ANCOVA Results for the outcome variable of percent of State-Owned Urban roadway miles in poor roughness condition (IRI ≥170 in/mile) in 2029

	Variable description	Coefficient	Standard error	T-statistic	P-value
Constant	N/A	44.236	N/A	N/A	N/A
Covariant effect	Five-year Pavement Rehabilitation Funding Level (millions of 2008 constant dollars)	−0.103	0.006	−17.90	<0.001
Treatment Trigger Policy effect (Deficiency Standard)	Low Condition Level Trigger	22.021	2.494	8.83	<0.001
	Medium Condition Level Trigger		0 (Control)		
	High Condition Level Trigger	−16.409	2.232	−7.35	<0.001
Interaction effect	Five-year Pavement Rehabilitation Funding Level*Low Condition Level Trigger	−0.058	0.010	−5.69	<0.001
	Five-year Pavement Rehabilitation Funding Level*High Condition Level Trigger	0.042	0.008	5.49	<0.001

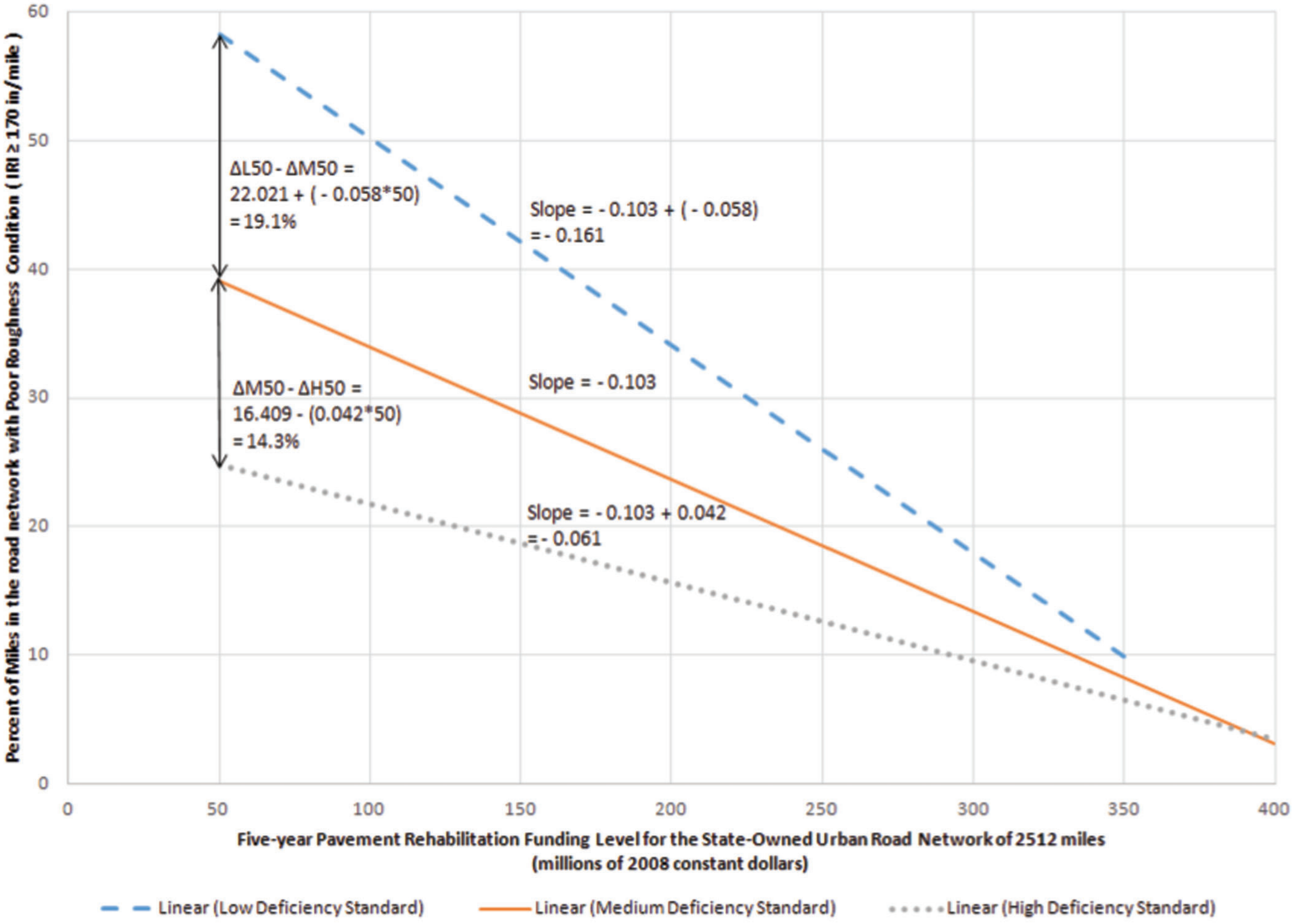


Figure 3.8 ANCOVA results for the outcome variable of percent of State-Owned Urban roadway miles in poor roughness condition (IRI ≥170 in/mile) in 2029.

3.4 Pavement Analysis Results for the State-Owned Rural Arterial Roadway Network

3.4.1 Pavement Roughness Condition of State-Owned Rural Arterials in 2029 due to Application of the Low Deficiency Standard for Triggering Pavement Rehabilitation During the 2009–2029 Period

Table 3.12 shows the pavement roughness condition for the Rural Interstate network, the Other State-Owned Rural Arterial network, and for the composite network: the State-Owned Rural Arterial network. The pavement roughness condition thresholds were reported as IRI <120 and IRI ≥170 because, according to the FHWA, pavements with IRI <120 can be considered to be in good roughness condition, and pavements of IRI ≥170 can be considered to be in poor roughness condition.

In plots like Figure 3.9, the pavements with the best IRI values are in the top band and the pavement with the worst IRI are in the lowest band.

Applying the Low Deficiency Standard for triggering pavement rehabilitation treatment on the State-Owned Rural Arterial network results in:

- Between the five-year funding levels of $10 million and $60 million, a dramatic increase in the percent of Rural Interstate miles with IRI <120 from 17.4% to 65.2%, as seen in Table 3.12 (Column 3) and Figure 3.10, however,
- The Other State Rural Arterial subset does not show as much of an improvement in the network-level roughness condition, as seen in Table 3.12 (Columns 5 and 6).
- Between the five-year funding levels of $10 million and $90 million, only an 11.1% reduction in the number of State Rural Arterial miles with IRI ≥170, from 23.7% to 12.6%. This is illustrated in Figure 3.9 and Table 3.12, Column 2.
- At a five-year funding level of $90 million, the percent of Other State Rural Arterial miles with IRI <120 is well below that of the Rural Interstate subset (20.8% for the Other State Rural Arterial subset vs 65.2% for the Rural Interstate subset) and,
- The percent of Other State Rural Arterial miles with IRI ≥170 is well above that of the Rural Interstate subset (15.1% for the Other State Rural Arterial subset vs 0.0% for the Rural Interstate subset).

The forthcoming results for the medium and High Deficiency Standards show that, for the State-Owned Rural Arterial system, the deficiency standard has a very dramatic impact on the network-level roughness condition. This could be because of the low level of funding that is required to address the pavement roughness of the State-Owned Rural Arterial system as compared to the level of funding that is needed by the State-Owned Urban system.

3.4.2 Pavement Roughness Condition of State-Owned Rural Arterials in 2029 due to Application of the Medium Deficiency Standard for Triggering Pavement Rehabilitation During the 2009–2029 Period

Applying the Medium Deficiency Standard for triggering pavement rehabilitation treatment on the State-Owned Rural Arterial network results in:

- Between the five-year funding levels of $10 million and $50 million, an increase in the percent of Rural Interstate miles with pavement roughness of IRI <120 from 44.3% to 89.8% as shown in Figure 3.12 and Table 3.13 (Column 3), and
- The percent of miles with IRI <120 for the Other State Rural Arterial subset is well below that of the Rural Interstate subset (Columns 3 and 5).
- At a $20 million five-year funding level, the percent of State Rural Arterial miles with pavement roughness of IRI ≥170 dropping below 10%, as seen in Table 3.13 (Column 2) and Figure 3.11.
- Beyond a five-year funding level of $80 million, no further improvement in the pavement condition of State Rural Arterials.

Important Analysis Observation:

- Compared to the Low Deficiency Standard, a much lower funding amount is needed to minimize the percent

TABLE 3.12
Pavement Roughness of State-Owned Rural Arterials in 2029 with different funding levels under the Low Deficiency Standard for triggering pavement rehabilitation during the 2009–2029 period

Five-year Pavement Rehabilitation Funding Level for the State-Owned Rural Arterial System (millions of 2008 constant dollars)	(1) Percent of State-Owned Rural Arterial miles with IRI <120	(2) Percent of State-Owned Rural Arterial miles with IRI ≥170	(3) Percent of Rural Interstate miles with IRI <120	(4) Percent of Rural Interstate miles with IRI ≥170	(5) Percent of Other State-Owned Rural Arterial roadway miles with IRI <120	(6) Percent of Other State-Owned Rural Arterial roadway miles with IRI ≥170
10	11.0	23.7	17.4	19.8	9.7	24.5
20	13.7	21.6	30.4	10.6	10.4	23.7
30	15.3	21.3	40.3	8.8	10.4	23.7
40	17.1	21.2	51.1	8.1	10.4	23.7
50	19.3	19.9	60.5	3.3	11.4	23.1
60	22.4	17.3	65.2	0.0	14.1	20.7
70	24.3	15.9	65.2	0.0	16.4	19.0
80	27.1	13.1	65.2	0.0	19.7	15.6
90	28.0	12.6	65.2	0.0	20.8	15.1

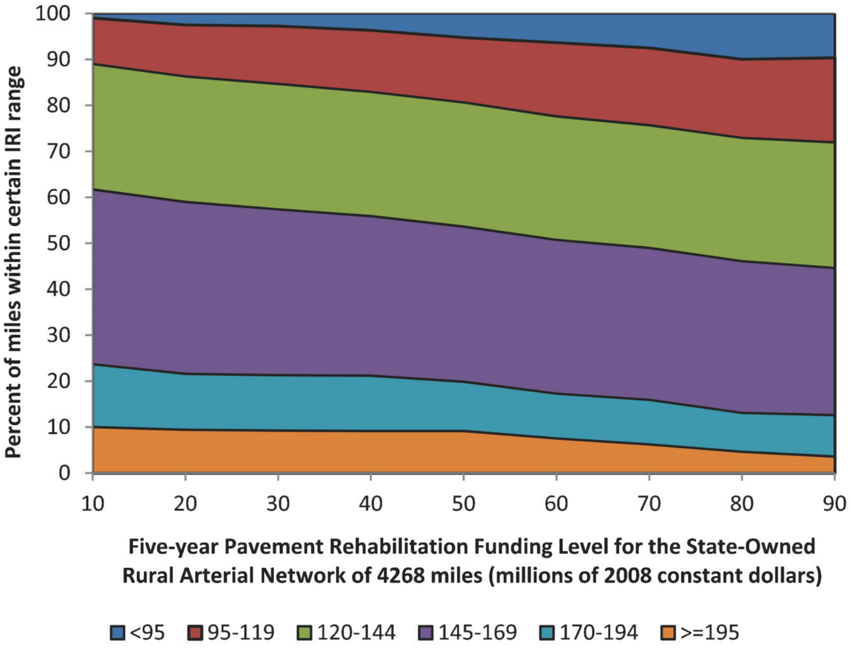


Figure 3.9 Pavement roughness of State Rural Arterials in 2029 with Low Deficiency Standard for triggering pavement rehabilitation.

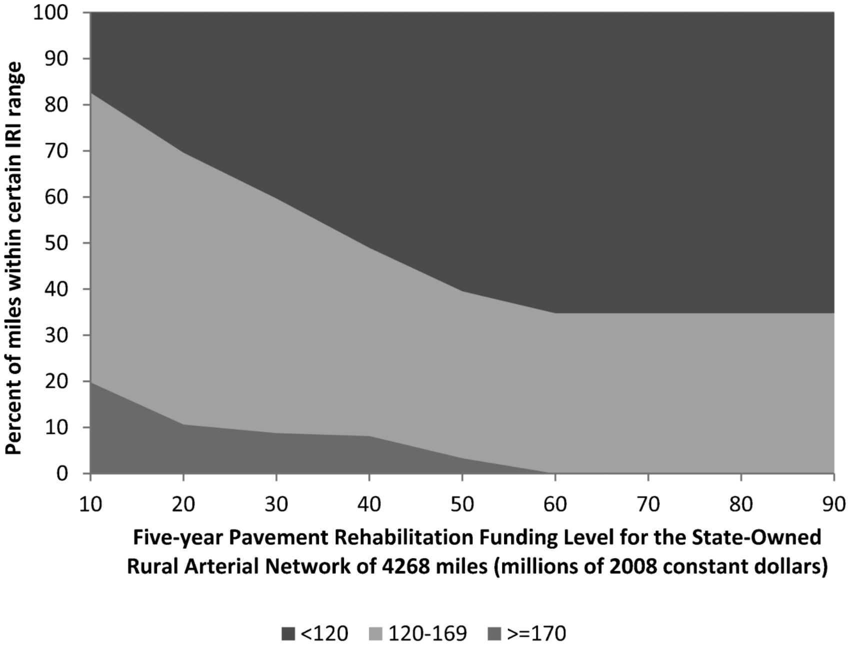


Figure 3.10 Pavement roughness of Rural Interstates in 2029 with Low Deficiency Standard for triggering pavement rehabilitation.

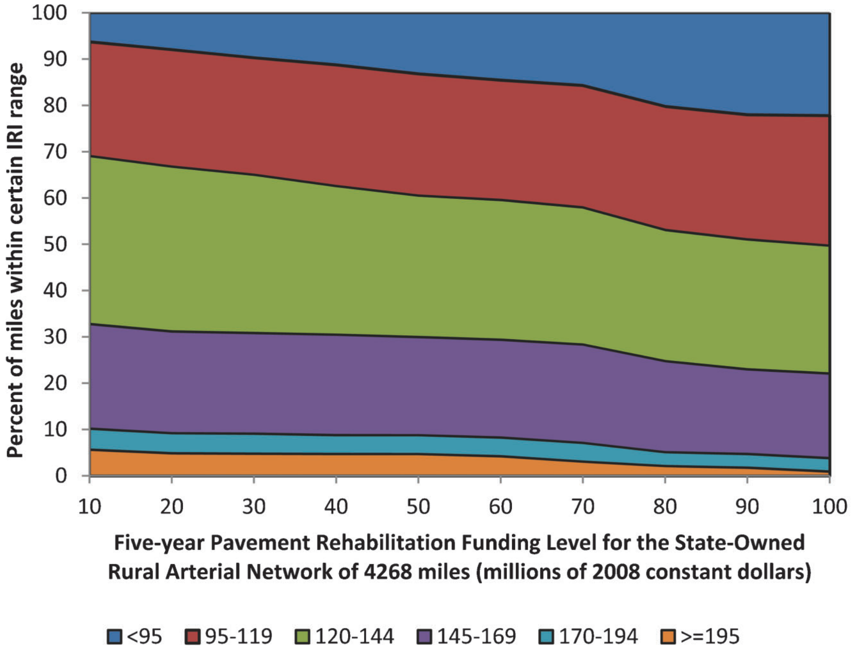


Figure 3.11 Pavement roughness of State Rural Arterials in 2029 with Medium Deficiency Standard for triggering pavement rehabilitation.

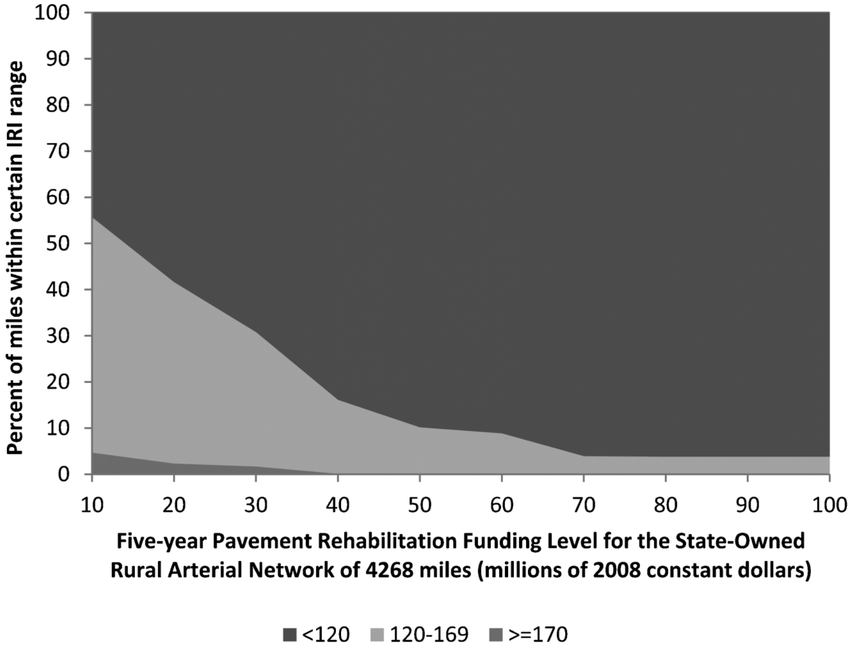


Figure 3.12 Pavement roughness of State Rural interstates in 2029 with Medium Deficiency Standard for triggering pavement rehabilitation.

TABLE 3.13
Pavement Roughness of State-Owned Rural Arterials in 2029 with different funding levels under the Medium Deficiency Standard for triggering pavement rehabilitation during the 2009–2029 period

Five-year Pavement Rehabilitation Funding Level for the State-Owned Rural Arterial System (millions of 2008 constant dollars)	(1) Percent of State-Owned Rural Arterial miles with IRI <120	(2) Percent of State-Owned Rural Arterial miles with IRI ≥170	(3) Percent of Rural Interstate miles with IRI <120	(4) Percent of Rural Interstate miles with IRI ≥170	(5) Percent of Other State-Owned Rural Arterial roadway miles with IRI <120	(6) Percent of Other State-Owned Rural Arterial roadway miles with IRI ≥170
10	30.9	10.2	44.3	4.7	28.3	11.3
20	33.2	9.2	58.3	2.3	28.3	10.5
30	35.0	9.1	69.2	1.7	28.3	10.5
40	37.4	8.8	83.9	0.1	28.4	10.5
50	39.5	8.8	89.8	0.0	29.7	10.5
60	40.4	8.3	91.1	0.0	30.6	9.9
70	42.0	7.1	96.1	0.0	31.5	8.5
80	46.9	5.1	96.2	0.0	37.3	6.1
90	48.9	4.7	96.2	0.0	39.8	5.6
100	50.3	3.8	96.2	0.0	41.4	4.6

of pavement miles in poor roughness condition. This is likely because implementing the Low Deficiency Standard causes the network's sections to join the category of the roughest pavements so fast that the agency has to spend a large amount of money to rehabilitate pavement sections and bring the network to a good state of repair.

3.4.3 Pavement Roughness Condition of State-Owned Rural Arterials in 2029 due to Application of the High Deficiency Standard for Triggering Pavement Rehabilitation During the 2009–2029 Period

Applying the High Deficiency Standard for triggering pavement rehabilitation treatment on the State-Owned Rural Arterial network results in:

- At a $10 million five-year funding level, the percent of State Rural Arterial road miles with pavement roughness of IRI ≥170 dropping below 10%, as shown in Figure 3.13 and Table 3.14 (Column 2) and,
- At that lowest funding level, the percent of Rural Interstate miles with IRI ≥170 is 2.3 as shown by Figure 3.14.

Important Analysis Observations:

- Tables 3.12–3.14 show that State Rural Arterials are highly sensitive to the deficiency standard being applied to trigger pavement rehabilitation.
- At a five-year funding level of $10 million and beyond, the higher the deficiency standard, the greater the percent of State Rural Arterial road miles join the IRI <120 pavement roughness category and the smaller the percent of miles join the IRI ≥170 category.
- For any funding level, switching from the low to the medium standard causes a greater magnitude decrease in the percent of State Rural Arterial road miles with pavement roughness of IRI ≥170 than switching from the medium to the High Deficiency Standard.

3.4.4 Summary of the performance of the pavement rehabilitation trigger policies (deficiency standards) in improving the roughness condition of State Rural Arterials

The ANCOVA analysis for the outcome variable of percent of State-Owned Rural Arterial roadway miles in good roughness condition is shown in Table 3.15 and illustrated in Figure 3.15. This analysis revealed that:

- Under the Low and Medium Level trigger policies, each increase of $10 million in the five-year pavement rehabilitation funding level causes an estimated increase of 2.2% in the number of State Rural Arterial road miles in good roughness condition.
- Under the High Level trigger policy, however, each increase of $10 million in the five-year pavement rehabilitation funding level causes an estimated increase of 1.2% in the number of State Rural Arterial road miles in good roughness condition.
- At any funding level, a change from the Medium Level to the Low Level policy would result in 19.6% fewer State Rural Arterial road miles in good condition.
- At the lowest five-year funding level of $10 million, a change from the Medium Level to the High Level policy would result in 27.6% more State Rural Arterial road miles in good condition.
- At the five-year funding level of $90 million, a change from the Medium Level to the High Level policy would result in 19.9% more State Rural Arterial road miles in good condition.

The ANCOVA analysis for the outcome variable of percent of State-Owned Rural Arterial roadway miles in poor roughness condition is shown in Table 3.16 and illustrated in Figure 3.16. This analysis confirmed that:

- There is a statistically significant interaction between the pavement rehabilitation funding and the choice of treatment trigger policy being implemented.

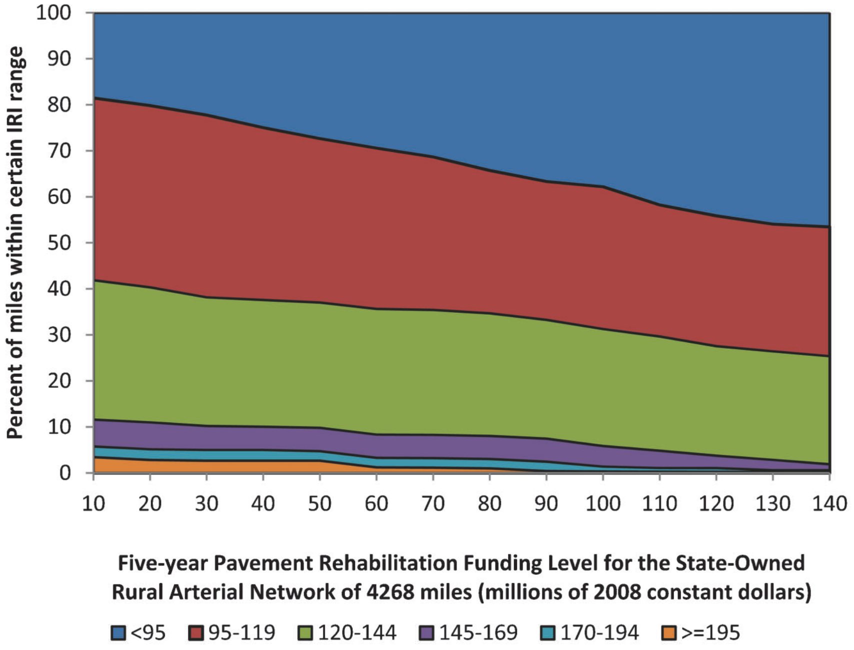


Figure 3.13 Pavement roughness of State Rural Arterials in 2029 with High Deficiency Standard for triggering pavement rehabilitation.

- If the Low Level trigger policy is implemented, each increase of $10 million in the five-year funding level causes an estimated decrease of 1.4% in the number of State Rural Arterial road miles in poor roughness condition.
- If the Medium Level trigger policy is implemented, each increase of $10 million in the five-year funding level causes an estimated decrease of 0.7% in the number of State Rural Arterial road miles in poor roughness condition.
- If the High Level trigger policy is implemented, each increase of $10 million in the five-year funding level causes an estimated decrease of 0.4% in the number of State Rural Arterial road miles in poor roughness condition.
- At the lowest five-year funding level of $10 million, a change from the Medium Level to the Low Level policy would result in 13.5% more State Rural Arterial road miles in poor condition, and

TABLE 3.14
Pavement Roughness of State-Owned Rural Arterials in 2029 with different funding levels under the High Deficiency Standard for triggering pavement rehabilitation during the 2009–2029 period

Five-year Pavement Rehabilitation Funding Level for the State-Owned Rural Arterial System (millions of 2008 constant dollars)	(1) Percent of State-Owned Rural Arterial miles with IRI <120	(2) Percent of State-Owned Rural Arterial miles with IRI ≥170	(3) Percent of Rural Interstate miles withIRI <120	(4) Percent of Rural Interstate miles withIRI ≥170	(5) Percent of Other State-Owned Rural Arterial roadway miles with IRI <120	(6) Percent of Other State-Owned Rural Arterial roadway miles with IRI ≥170
10	58.1	5.8	65.9	2.3	56.6	6.4
20	59.7	5.2	75.4	2.3	56.6	5.7
30	61.8	5.0	85.0	1.7	57.3	5.6
40	62.4	5.0	88.6	1.7	57.3	5.6
50	63.0	4.7	91.7	0.1	57.4	5.6
60	64.3	3.3	91.7	0.1	59.0	3.9
70	64.6	3.2	91.9	0.0	59.2	3.9
80	65.3	3.0	93.5	0.0	59.8	3.6
90	66.7	2.5	95.9	0.0	61.0	2.9
100	68.7	1.4	97.4	0.0	63.1	1.7
110	70.3	1.1	100.0	0.0	64.6	1.3
120	72.4	1.1	100.0	0.0	67.1	1.3
130	73.6	0.6	100.0	0.0	68.4	0.7
140	74.6	0.6	100.0	0.0	69.7	0.7

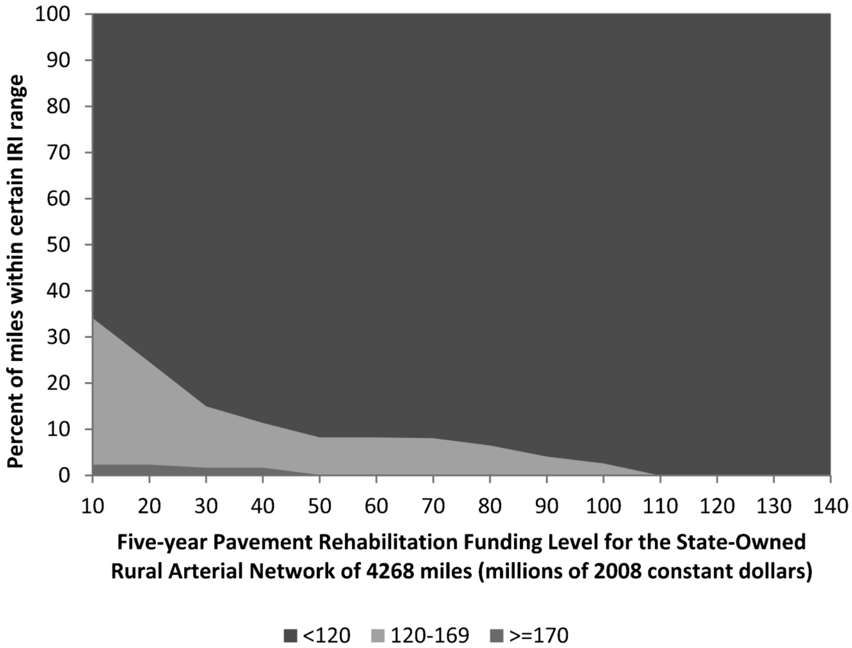


Figure 3.14 Pavement roughness of Rural Interstates in 2029 with High Deficiency Standard for triggering pavement rehabilitation.

- A change from the Medium Level to the High Level policy would result in 4.75% fewer State Rural Arterial road miles in poor condition.

3.5 Pavement Analysis Results for the Federal-Aid Urban Roadway Network

3.5.1 Pavement Roughness Condition of Federal-Aid Urban Roads in 2029 due to Application of the Low Deficiency Standard for Triggering Pavement Rehabilitation During the 2009–2029 Period

Table 3.17 shows the pavement roughness condition for the Federal-Aid Urban network. The network condition shown in Table 3.17 is broken down into the Urban Arterial/Urban Major Collector network components and alternatively into the State-Owned/Non State-Owned components. Because the Federal-Aid Urban network encompasses the entire State-Owned Urban roadway network, one should expect that this network would need a greater funding level than the subset State-Owned Urban network to achieve good roughness condition for its pavements.

The pavement roughness condition thresholds were reported as IRI <120 and IRI ≥170 because, according to the FHWA, pavements with IRI <120 can be considered to be in good roughness condition, and pavements of IRI ≥170 can be considered to be in poor roughness condition.

In plots like Figure 3.17, the pavements with the best IRI values are in the top band and the pavement with the worst IRI are in the lowest band.

TABLE 3.15
ANCOVA Results for the outcome variable of percent of State-Owned Rural Arterial Road Miles in Good Roughness Condition (IRI < 120 in/mile) in 2029

	Variable description	Coefficient	Standard error	T-statistic	P-value
Constant	N/A	28.452	N/A	N/A	N/A
Covariant effect	Five-year Pavement Rehabilitation Funding Level (millions of 2008 constant dollars)	0.218	0.006	34.51	<0.001
Treatment Trigger Policy effect (Deficiency Standard)	Low Condition Level Trigger	−19.559	0.348	−56.18	<0.001
	Medium Condition Level Trigger	0 (Control)			
	High Condition Level Trigger	28.515	0.599	47.57	<0.001
Interaction effect	Five-year Pavement Rehabilitation Funding Level High Condition Level Trigger	−0.096	0.008	−11.94	<0.001

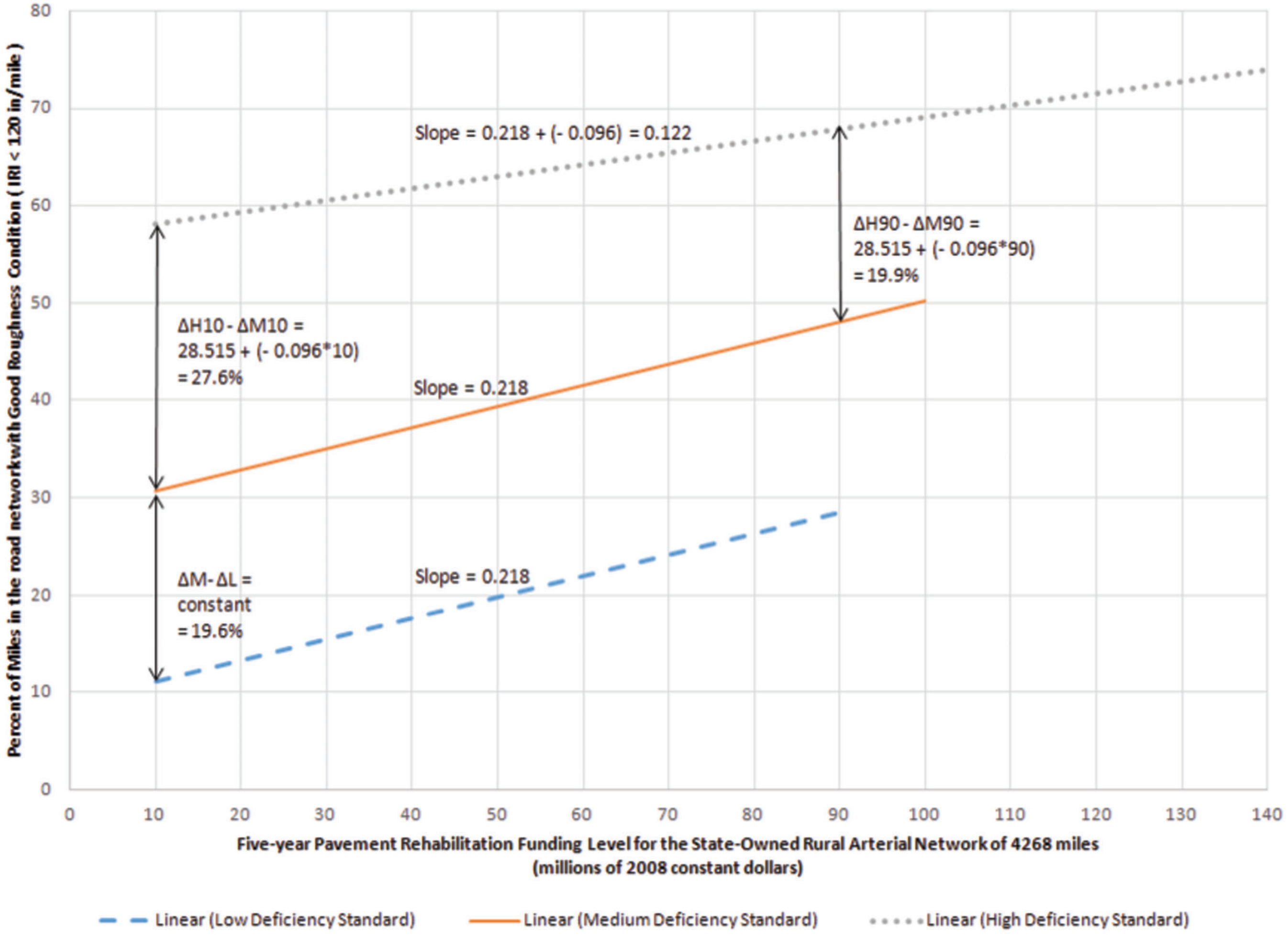


Figure 3.15 ANCOVA results for the outcome variable of percent of State-Owned Rural Arterial road miles in good roughness condition (IRI <120 in/mile) in 2029.

TABLE 3.16
ANCOVA Results for the outcome variable of percent of State-Owned Rural Arterial Road Miles in Poor Roughness Condition (IRI $\geq$ 170 in/mile) in 2029

	Variable description	Coefficient	Standard error	T-statistic	P-value
Constant	N/A	11.333	N/A	N/A	N/A
Covariant effect	Five-year Pavement Rehabilitation Funding Level (millions of 2008 constant dollars)	−0.070	0.007	−9.33	<0.001
Treatment Trigger Policy effect (Deficiency Standard)	Low Condition Level Trigger	14.228	0.675	21.08	<0.001
	Medium Condition Level Trigger		0 (Control)		
	High Condition Level Trigger	−5.006	0.600	−8.34	<0.001
Interaction effect	Five-year Pavement Rehabilitation Funding Level*Low Condition Level Trigger	−0.071	0.011	−6.22	<0.001
	Five-year Pavement Rehabilitation Funding Level High Condition Level Trigger	0.026	0.009	2.95	0.007

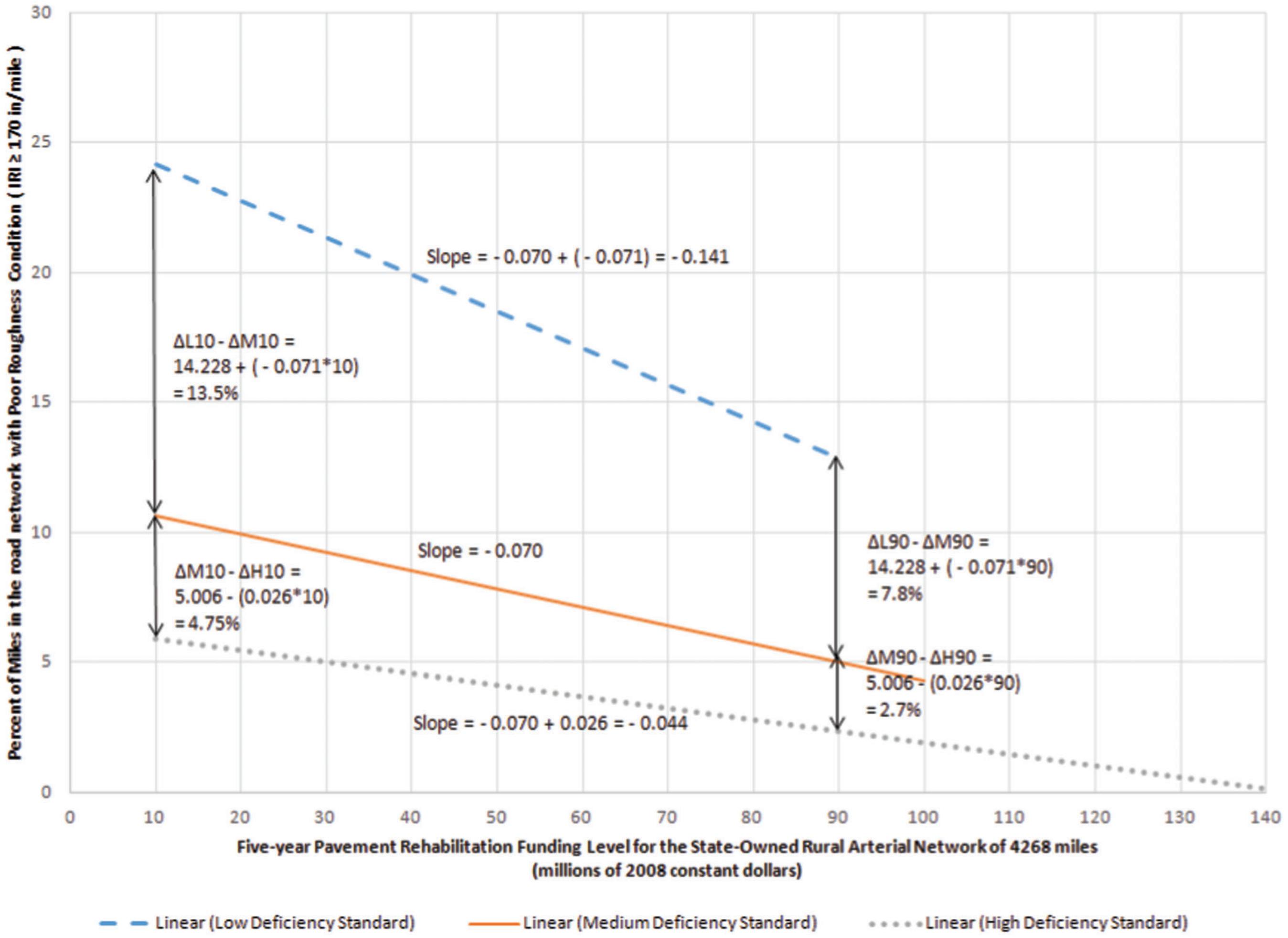


Figure 3.16 ANCOVA results for the outcome variable of percent of State-Owned Rural Arterial road miles in poor roughness condition (IRI ≥170 in/mile) in 2029.

Applying the Low Deficiency Standard for triggering pavement rehabilitation treatment on the Federal-Aid Urban road network results in:

- Most of the miles in the Federal-Aid Urban Major Collector subset having a pavement roughness of IRI ≥170 (Table 3.17 Column 6).
- A five-year funding level of $550 million being necessary for the Federal-Aid Urban System so that the Federal-Aid Urban Arterial subset has less than one third of its roadway miles with a pavement roughness of IRI ≥170 (Column 4).
- At the five-year funding level of $550 million, the percent of State-Owned Urban road miles with a pavement roughness of IRI ≥170 dropping to 6.8% (Column 8) however,
- The percent of Non-State-Owned Urban road miles with pavement roughness of IRI ≥170 remaining high at 59.4% (Column 10).

Important Analysis Observation:

- As can be seen in Figure 3.17, adopting the Low Deficiency Standard for triggering pavement rehabilitation is a bad strategy for the Federal-Aid Urban roadway network as compared to adopting the Medium Deficiency Standard and the High Deficiency Standard (see Tables 3.18 and 3.19). It seems to result in a situation where the network's sections join the category of the roughest pavements faster than the agency can rehabilitate pavement sections to bring that network to a good state of repair.

3.5.2 Pavement Roughness Condition of Federal-Aid Urban roads in 2029 due to application of the Medium Deficiency Standard for triggering Pavement Rehabilitation during the 2009–2029 period

Applying the Medium Deficiency Standard for triggering pavement rehabilitation treatment on the Federal-Aid Urban road network results in:

- A five-year funding level of $150 million or more being necessary to make some improvement in the pavement roughness condition of Federal-Aid Urban roads, as seen in Table 3.18 and Figure 3.18.
- Between the five-year funding levels of $50 million and $650 million for the Federal-Aid Urban road network, an increase in the percent of Urban Arterial road miles with pavement roughness of IRI <120, from 9.4% to 55.0% (Table 3.18 Column 3), and

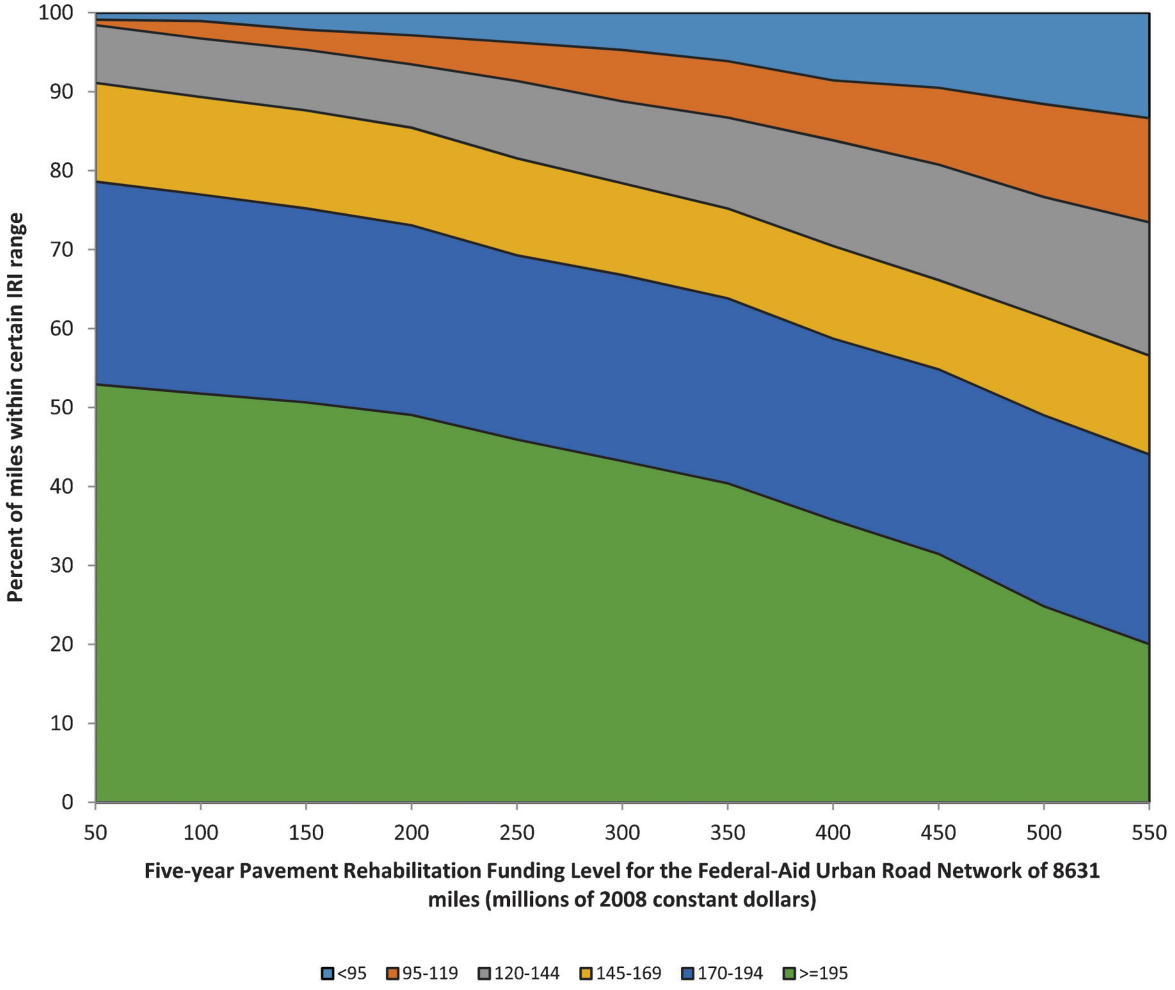


Figure 3.17 Pavement roughness of Federal-Aid Urban roads in 2029 under the Low Deficiency Standard for triggering pavement rehabilitation.

TABLE 3.17
Pavement Roughness of Federal-Aid Urban roads with different funding levels in 2029 under the Low Deficiency Standard for triggering pavement rehabilitation during the 2009–2029 period

Five-year Pavement Rehabilitation Funding Level for the Federal-Aid Urban System (millions of 2008 constant dollars)	(1) Percent of Federal-Aid Urban roadway miles with IRI <120	(2) Percent of Federal-Aid Urban roadway miles with IRI ≥170	(3) Percent of Federal-Aid Urban Arterial miles with IRI <120	(4) Percent of Federal-Aid Urban Arterial miles with IRI ≥170	(5) Percent of Federal-Aid Urban Major Collector miles with IRI <120	(6) Percent of Federal-Aid Urban Major Collector miles with IRI ≥170	(7) Percent of State-Owned miles with IRI <120	(8) Percent of State-Owned miles with IRI ≥170	(9) Percent of Non-State-Owned miles with IRI <120	(10) Percent of Non-State-Owned miles with IRI ≥170
50	1.4	78.6	1.4	71.0	1.4	91.7	1.4	56.4	1.4	87.7
100	3.2	77.0	4.3	68.5	1.5	91.7	7.2	51.7	1.6	87.3
150	4.7	75.2	6.5	65.8	1.5	91.5	11.4	47.3	1.9	86.7
200	6.5	73.1	9.4	62.9	1.5	90.7	17.1	41.9	2.2	85.9
250	8.6	69.3	12.0	59.5	2.1	86.2	21.1	36.8	3.5	82.6
300	11.2	66.8	15.6	55.7	2.3	86.0	26.7	31.7	4.9	81.2
350	13.3	63.8	19.7	51.5	2.8	85.2	30.8	27.6	6.1	78.7
400	16.2	58.7	24.1	45.8	3.7	81.0	35.0	23.2	8.4	73.3
450	19.2	54.8	28.0	40.3	4.0	79.9	37.9	18.8	11.5	69.7
500	23.3	49.0	32.9	33.3	6.8	76.3	46.1	9.4	13.9	65.3
550	26.5	44.1	35.2	28.5	11.5	70.9	48.5	6.8	17.5	59.4

TABLE 3.18
Pavement Roughness of Federal-Aid Urban roads with different funding levels in 2029 under the Medium Deficiency Standard for triggering pavement rehabilitation during the 2009–2029 period

Five-year Pavement Rehabilitation Funding Level for the Federal-Aid Urban System (millions of 2008 constant dollars)	(1) Percent of Federal-Aid Urban roadway miles with IRI <120	(2) Percent of Federal-Aid Urban roadway miles with IRI ≥170	(3) Percent of Federal-Aid Urban Arterial miles with IRI <120	(4) Percent of Federal-Aid Urban Arterial miles with IRI ≥170	(5) Percent of Federal-Aid Urban Major Collector miles with IRI <120	(6) Percent of Federal-Aid Urban Major Collector miles with IRI ≥170	(7) Percent of State-Owned miles with IRI <120	(8) Percent of State-Owned miles with IRI ≥170	(9) Percent of Non-State-Owned miles with IRI <120	(10) Percent of Non-State-Owned miles with IRI ≥170
50	6.9	51.8	9.4	41.7	2.6	69.3	16.6	40.2	3.0	56.6
100	8.3	50.3	11.4	39.5	2.8	69.0	19.9	36.5	3.4	55.9
150	10.1	48.4	14.2	37.1	2.9	67.9	24.8	33.0	4.0	54.8
200	12.7	45.5	16.6	35.1	4.1	63.4	28.9	30.1	6.0	51.8
250	14.8	43.0	21.0	31.8	4.9	62.3	35.3	26.3	6.4	49.8
300	17.8	40.3	25.3	27.5	5.7	62.3	42.0	22.6	7.9	47.5
350	21.0	37.4	29.8	24.0	5.7	60.6	48.0	18.6	9.9	45.2
400	24.0	34.9	33.4	21.3	5.9	58.5	52.0	16.5	12.5	42.5
450	27.3	30.1	39.8	15.6	7.4	55.3	57.9	12.6	14.7	37.3
500	30.8	27.3	44.4	11.7	7.8	54.1	64.7	10.2	16.9	34.2
550	34.8	22.7	48.8	6.8	10.6	50.1	73.1	2.8	19.1	30.8
600	38.8	17.0	51.2	4.0	17.3	39.5	74.3	1.8	24.2	23.2
650	43.0	11.0	55.0	0.3	22.4	29.4	76.3	0.3	29.3	15.4

TABLE 3.19
Pavement Roughness of Federal-Aid Urban roads with different funding levels in 2029 under the High Deficiency Standard for triggering pavement rehabilitation during the 2009–2029 period

Five-year Pavement Rehabilitation Funding Level for the Federal-Aid Urban System (millions of 2008 constant dollars)	(1) Percent of Federal-Aid Urban roadway miles with IRI <120	(2) Percent of Federal-Aid Urban roadway miles with IRI ≥170	(3) Percent of Federal-Aid Urban Arterial miles with IRI <120	(4) Percent of Federal-Aid Urban Arterial miles with IRI ≥170	(5) Percent of Federal-Aid Urban Major Collector miles with IRI <120	(6) Percent of Federal-Aid Urban Major Collector miles with IRI ≥170	(7) Percent of State-Owned miles with IRI <120	(8) Percent of State-Owned miles with IRI ≥170	(9) Percent of Non-State-Owned miles with IRI <120	(10) Percent of Non-State-Owned miles with IRI ≥170
50	17.1	34.0	21.0	32.2	10.3	37.3	29.6	29.0	11.4	36.1
100	18.0	31.5	22.4	30.5	10.4	33.2	31.6	26.4	11.9	33.6
150	21.0	28.8	25.7	27.9	12.9	30.5	35.7	23.6	14.4	31.0
200	24.9	25.7	29.7	25.1	16.6	27.4	40.9	20.9	17.7	27.7
250	27.8	23.3	34.3	21.0	16.7	26.7	45.4	17.6	20.1	25.7
300	30.7	21.3	37.8	19.2	18.4	24.9	51.2	14.9	21.8	23.9
350	34.9	17.9	43.8	14.5	19.4	23.9	56.9	11.5	25.3	20.5
400	37.8	15.7	48.3	12.3	19.7	21.5	63.1	9.4	27.4	18.3
450	41.2	13.4	52.6	9.7	20.4	19.9	67.7	7.3	30.2	15.9
500	44.8	11.6	57.8	7.8	20.9	18.2	73.0	5.7	33.2	14.1
550	46.3	9.7	61.2	5.2	21.4	17.4	76.5	3.9	33.8	12.0
600	49.3	7.2	65.7	4.1	21.5	12.6	81.6	3.1	35.9	9.0
650	53.6	5.5	72.2	3.0	22.2	9.7	88.5	1.7	39.3	7.0
700	58.7	3.8	78.5	2.1	24.0	6.7	90.3	1.0	45.7	5.0
750	60.1	2.6	81.1	0.5	24.4	6.3	92.0	0.6	47.0	3.5
800	65.2	0.2	83.6	0.2	33.5	0.3	92.9	0.5	53.9	0.2

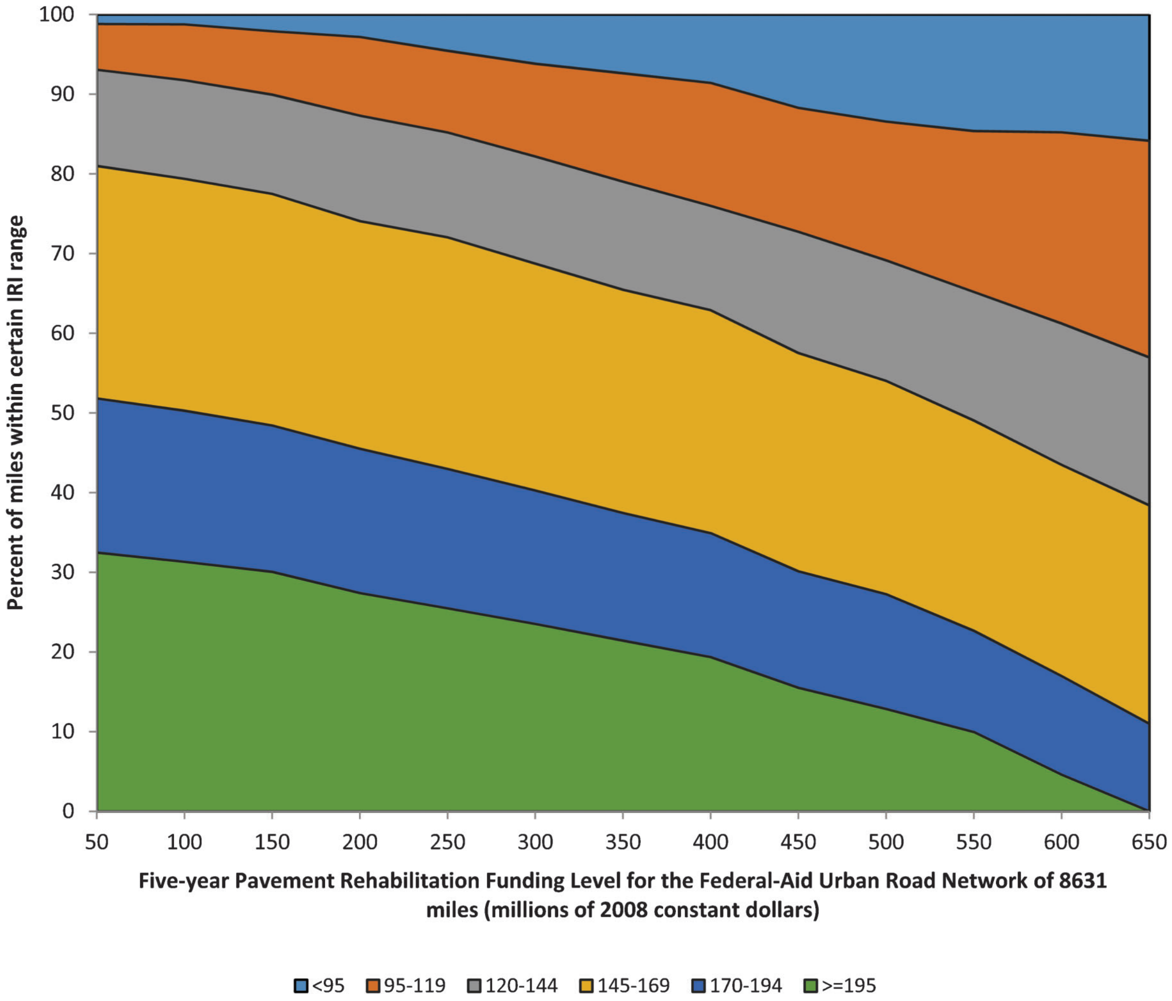


Figure 3.18 Pavement roughness of Federal-Aid Urban roads in 2029 under the Medium Deficiency Standard for triggering pavement rehabilitation.

- An increase in the percent of Urban Major Collector road miles with pavement roughness of IRI <120, from 2.6% to 22.4% (Column 5).
- Between the five-year funding levels of $50 million and $650 million for the Federal-Aid Urban road network, an increase in the percent of State-Owned Urban road miles with pavement roughness of IRI <120, from 16.6% to 76.3% (Column 7) and
- An increase in the percent of Non-State-Owned Urban road miles with pavement roughness of IRI <120, from 3.0% to 29.3% (Column 9).
- A five-year funding level of $650 million being necessary for the Federal-Aid Urban roadway network to have only 11% of its pavement miles in the roughness category of IRI ≥170 (Column 2).
- At the five-year funding level of $650 million, the percent of Federal-Aid Urban Arterial miles with IRI ≥170 reaching 0.3%, (Column 4) and the percent of Federal-Aid Urban Major Collector miles with IRI ≥170 reaching 29.4% (Column 6), additionally
- The percent of State-Owned Urban road miles with pavement roughness of IRI ≥170 reaching 0.3% (Column 8) and the percent of Non-State-Owned Urban road miles with pavement roughness of IRI ≥170 reaching 15.4% (Column 10).

3.5.3 Pavement Roughness Condition of Federal-Aid Urban roads in 2029 due to application of the High Deficiency Standard for triggering Pavement Rehabilitation during the 2009–2029 period

Applying the High Deficiency Standard for triggering pavement rehabilitation treatment on the Federal-Aid Urban road network results in:

- As the funding level increases, the percent of Federal-Aid Urban road miles with IRI <120 increasing at a steep linear rate, as Figure 3.19 and Table 3.19 (Column 1) show, and
- A faster increase in the percent of road miles with pavement roughness of IRI <120 for the Urban Arterial subset than for its complementary subset—the Urban Major Collector subset.
- A five-year funding level of $550 million being needed for the Federal-Aid Urban roadway network to have less

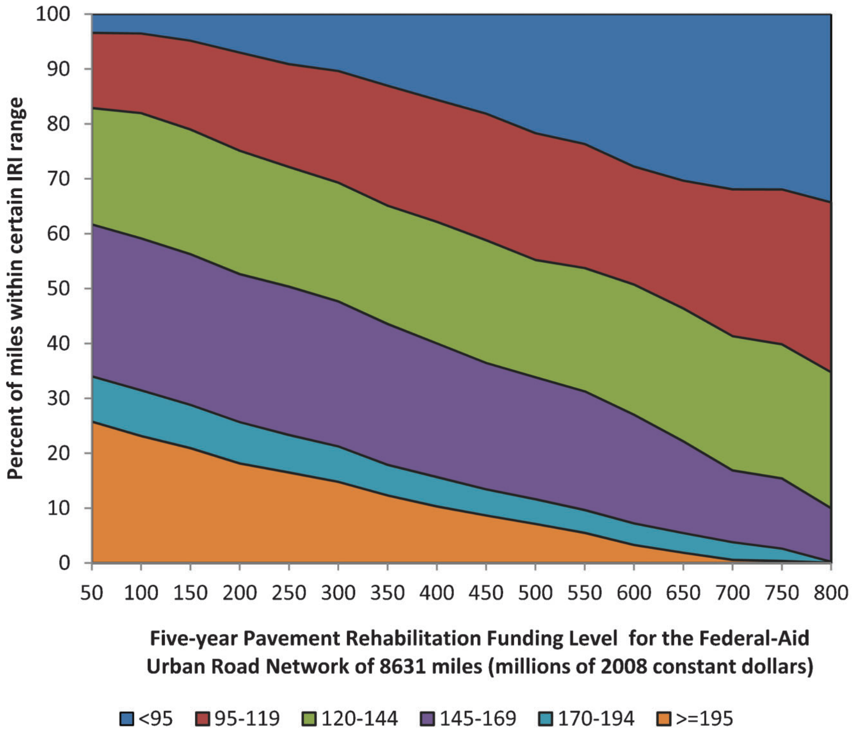


Figure 3.19 Pavement roughness of Federal-Aid Urban roads in 2029 under the High Deficiency Standard for triggering pavement rehabilitation.

than 10% of its miles in the pavement roughness category of IRI ≥170, as shown in Table 3.19 Column 2.

- At the five-year funding level of $550 million, the percent of Federal-Aid Urban Arterial miles with IRI ≥170 reaching 5.2% (Column 4), and the percent of Federal-Aid Urban Major Collector miles with IRI ≥170 reaching 17.4% (Column 6). Additionally,
- The percentages of State-Owned Urban and Non-State-Owned Urban road miles with IRI ≥170 reaching 3.9% and 12.0%, respectively (Columns 8 and 10).
- Between the five-year funding levels of $50 million and $800 million for the Federal-Aid Urban road network, the percent of Urban Arterial road miles with pavement roughness of IRI <120 increasing from 21.0% to 83.6% (Column 3), and the percent of Urban Major Collector road miles with pavement roughness of IRI<120 increasing from 10.3% to 33.5% (Column 5). Similarly,
- The percent of State-Owned Urban road miles with pavement roughness of IRI <120 increasing from 29.6% to 92.9% (Column 7), and the percent of Non-State-Owned Urban road miles with pavement roughness of IRI<120 increasing from 11.4% to 53.9% (Column 9).

Important Analysis Observations:

- It can be seen from Tables 3.17–3.19 that Federal-Aid Urban roads are very sensitive to the deficiency standard being applied to trigger pavement rehabilitation. At a five-year funding level of $50 million and beyond, the higher the deficiency standard, the greater the percent of miles join the IRI<120 pavement roughness category and the smaller the percent of miles join the IRI≥170 category.
- For any funding level, switching from the low to the Medium Deficiency Standard has an effect of greater magnitude in decreasing the percent of Federal-Aid Urban road miles in poor pavement roughness condition than switching from the medium to the High Deficiency Standard.
- Also, switching from the medium to the High Deficiency Standard has an effect of greater magnitude in increasing the percent of Federal-Aid Urban road miles in good pavement roughness condition than switching from the low to the Medium Deficiency Standard.

3.5.4 Summary of the performance of pavement rehabilitation trigger policies (deficiency standards) in improving the roughness condition of Federal-Aid Urban roads

The ANCOVA analysis for the outcome variable of percent of Federal-Aid Urban roadway miles in good roughness condition is shown in Table 3.20 and illustrated in Figure 3.20. This analysis revealed that:

- Under the Medium and High Level trigger policies, each increase of $10 million in the five-year pavement rehabilitation funding level causes an estimated increase of 0.6% in the number of Federal-Aid Urban road miles in good roughness condition.
- Under the Low Level trigger policy, however, each increase of $10 million in the five-year pavement rehabilitation funding level causes an estimated increase of 0.5% in the number of Federal-Aid Urban roadway miles in good roughness condition.
- At the lowest five-year funding level of $50 million, a change from the Medium Level policy to the Low Level policy would result in 3.6% fewer Federal-Aid Urban roadway miles in good condition.

TABLE 3.20
ANCOVA Results for the outcome variable of percent of Federal-Aid Urban Roadway Miles in Good Roughness Condition (IRI <120 in/mile) in 2029

	Variable description	Coefficient	Standard error	T-statistic	P-value
Constant	N/A	0.136	N/A	N/A	N/A
Covariant effect	Five-year Pavement Rehabilitation Funding Level (millions of 2008 constant dollars)	0.063	0.001	55.69	<0.001
Treatment Trigger Policy effect (Deficiency Standard)	Low Condition Level Trigger	−2.863	0.998	−2.87	0.007
	Medium Condition Level Trigger		0 (Control)		
	High Condition Level Trigger	12.376	0.493	25.09	<0.001
Interaction effect	Five-year Pavement Rehabilitation Funding Level *Low Condition Level Trigger	−0.014	0.003	−5.01	<0.001

- At any funding level, a change from the Medium Level to the High Level trigger policy would result in 12.4% more Federal-Aid Urban roadway miles in good condition.

The ANCOVA analysis for the outcome variable of percent of Federal-Aid Urban roadway miles in poor roughness condition is shown in Table 3.21 and illustrated in Figure 3.21. This analysis revealed that:

- Under the Low and Medium Level trigger policies, each increase of $10 million in the five-year pavement rehabilitation funding level causes an estimated decrease of 0.7% in the number of Federal-Aid Urban roadway miles in poor roughness condition.
- Under the High Level trigger policy, however, each increase of $10 million in the five-year pavement rehabilitation funding level causes an estimated decrease

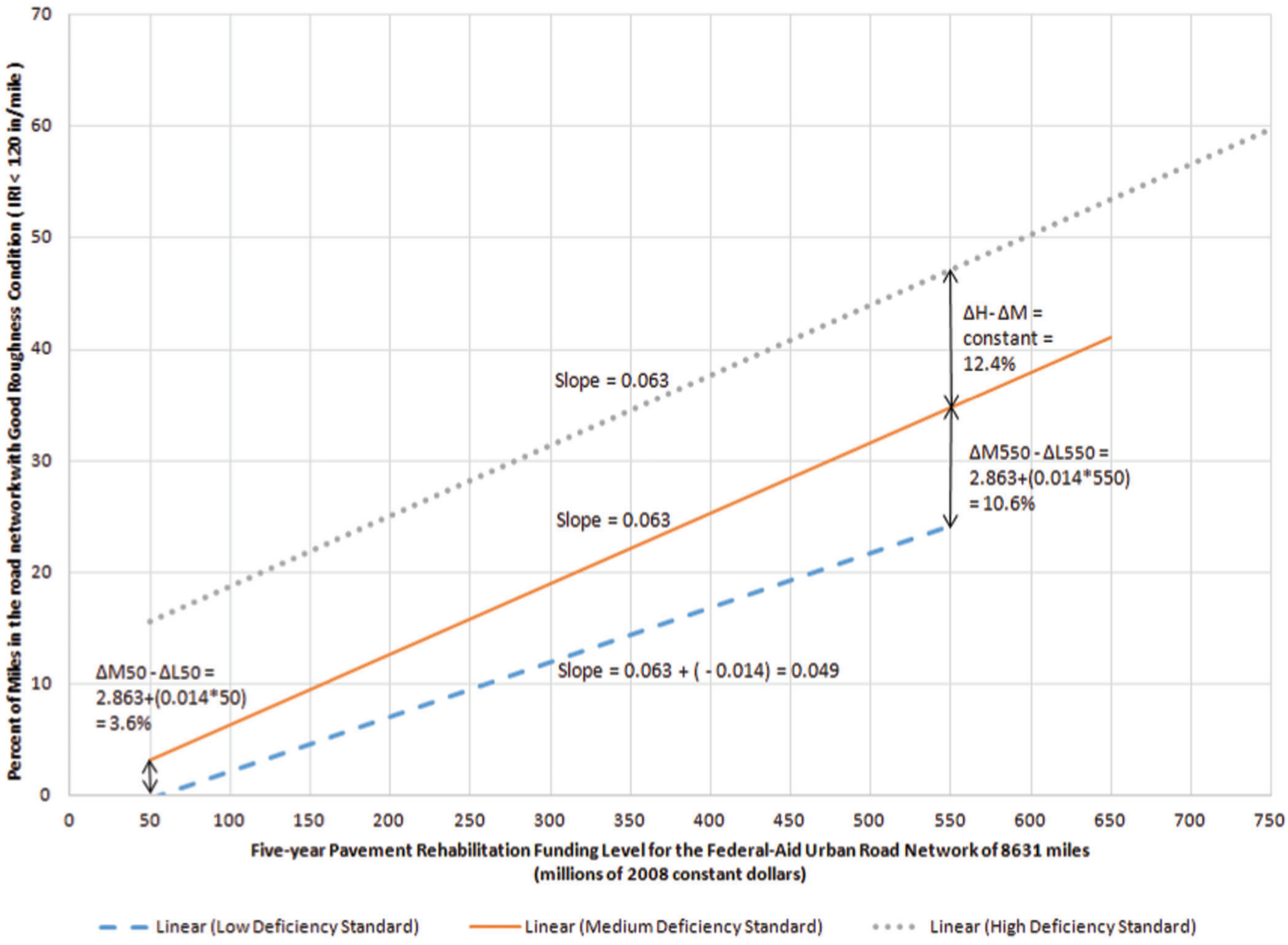


Figure 3.20 ANCOVA results for the outcome variable of percent of Federal-Aid Urban roadway miles in good roughness condition (IRI <120 in/mile) in 2029.

TABLE 3.21
ANCOVA Results for the outcome variable of percent of Federal-Aid Urban roadway miles in poor roughness condition (IRI ≥170 in/mile) in 2029

	Variable description	Coefficient	Standard error	T-statistic	P-value
Constant	N/A	58.852	N/A	N/A	N/A
Covariant effect	Five-year Pavement Rehabilitation Funding Level (millions of 2008 constant dollars)	−0.067	0.002	−31.18	<0.001
Treatment Trigger Policy effect (Deficiency Standard)	Low Condition Level Trigger	25.864	0.761	33.98	<0.001
	Medium Condition Level Trigger	0 (Control)			
	High Condition Level Trigger	−23.947	1.326	−18.06	<0.001
Interaction effect	Five-year Pavement Rehabilitation Funding Level * High Condition Level Trigger	0.022	0.003	7.52	<0.001

of 0.5% in the number of Federal-Aid Urban roadway miles in poor roughness condition.

- At the lowest five-year funding level of $50 million, a change from the Medium Level to the High Level policy would result in 22.85% fewer Federal-Aid Urban roadway miles in poor condition.
- At any funding level, a change from the Medium Level to the Low Level policy would result in 25.9%

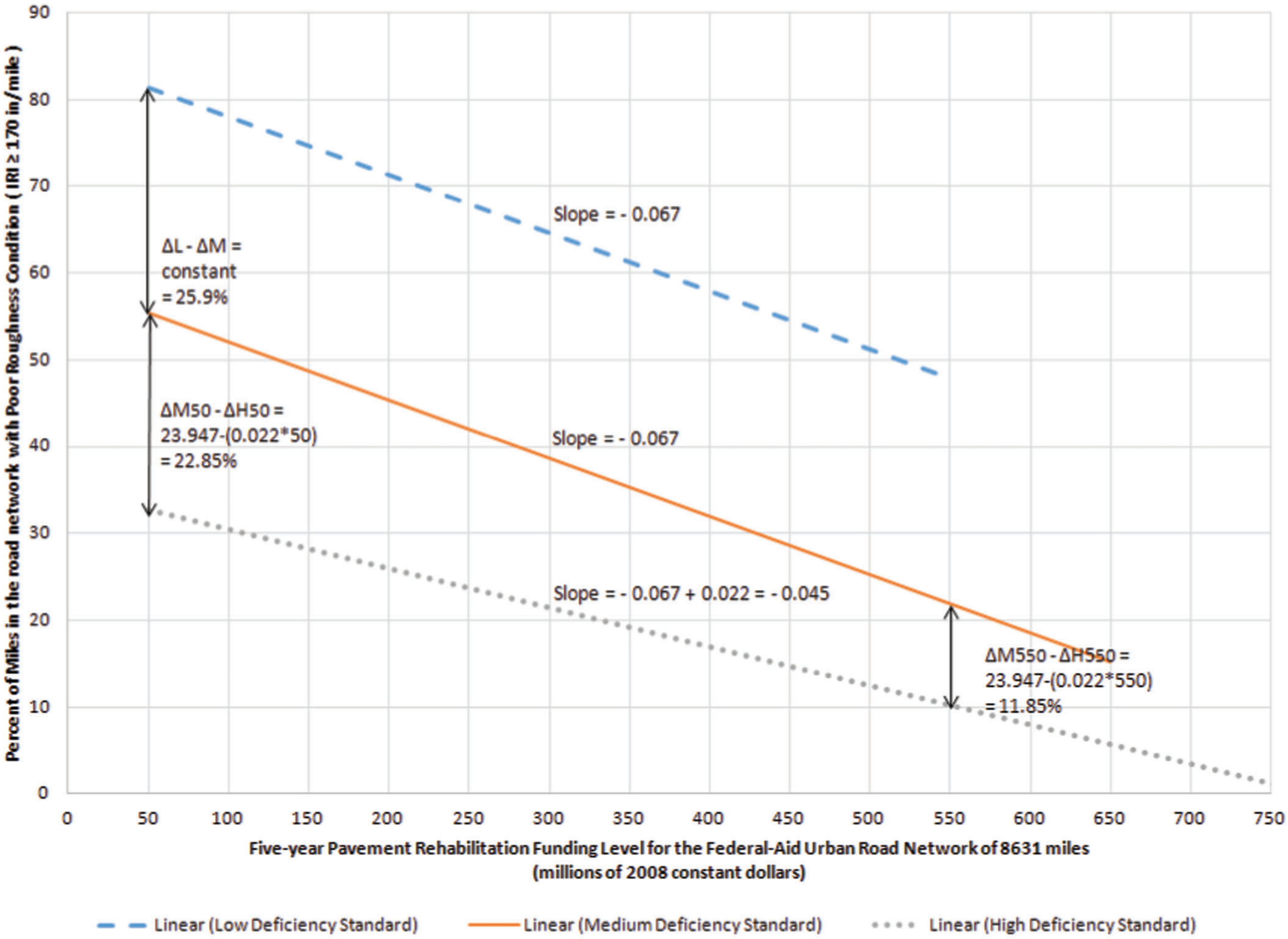


Figure 3.21 ANCOVA results for the outcome variable of percent of Federal-Aid Urban roadway miles in poor roughness condition (IRI ≥170 in/mile) in 2029.

more Federal-Aid Urban roadway miles in poor condition.

4. MOBILITY ASSET ANALYSIS RESULTS

4.1 Introduction

The purpose of this analysis is to provide a projection of the long-term consequences on a network's mobility condition of changing lane addition trigger values and varying the budget available for these treatments. A trigger value (or deficiency standard) is the rating of a relevant metric at which an appropriate treatment should be undertaken. If the deficiency standard is set high, this means that a treatment is triggered earlier, or at a better condition level. The consequence is a likely a better network condition, but this may be achieved at a higher cost. Conversely, a Low Deficiency Standard means that treatments are triggered later on, at worse condition levels. Waiting longer to treat sections may seem like a plausible strategy to reduce agency expenditures, but adopting this strategy in the long term can result in widespread poor conditions in the network, which are expensive to reverse. The analyses in this project investigate the tradeoffs and long-term trends involved in changing the trigger value at various budget levels.

The research team used HERS-ST software to observe how the trigger levels defined for lane additions affect the peak hour mobility condition for the State-Owned Urban network and the Federal-Aid Urban Highway network.

Indiana's 2009 Highway Performance Monitoring System (HPMS) sample section data was used as the input to HERS-ST. The HERS-ST software takes HPMS data as input and, based upon certain data items, identifies deficiencies in roadways assets:

- pavement assets (Pavement Serviceability Rating)
- mobility condition (peak hour V/C ratio), and
- geometric alignment (horizontal alignment adequacy and vertical alignment adequacy).

The HERS-ST software provides the flexibility of changing the deficiency standards. Changing the deficiency (trigger) levels in HERS-ST influences the network condition. Once deficient sections are identified, the HERS-ST software prioritizes potential improvements using a benefit-cost ratio. The future benefits resulting from an improvement consist of

- user cost savings due to reductions in travel time,
- vehicle operating cost savings, and
- fewer collisions.

After implementation of the improvements, HERS-ST recalculates road section conditions and aggregates them to reflect a system's condition in terms of percent of sections exceeding a certain performance threshold.

4.2 Use of HERS-ST Software to Generate Mobility Analysis Results

Table 4.1 shows three lane addition trigger sets (mobility deficiency standards) that were defined to represent the mobility condition at which *lane addition* can be triggered. The trigger values influence the network condition by determining which sections in the input data are identified as deficient. The trigger values vary by road classification as a way to approximate that a higher priority may be placed on addressing peak hour congestion on roadways with a higher functional class.

It should be noted that, unlike the case with the pavement deficiency standards, the "Medium" Deficiency Standard is not meant to represent the strategy that INDOT might currently be following to trigger lane additions for Indiana roadways.

While it is common knowledge that there are other ways to mitigate congestion, including demand management through congestion pricing, designation of high occupancy vehicle lanes, or installation of ITS systems for the most congested roads to inform drivers of mobility conditions, the implementation of these strategies was impossible to simulate in the HERS-ST software to study their impact.

The High, Medium and Low mobility deficiency standards were applied to two networks: the State Urban roadway network and the Federal-Aid Urban roadway network.

The analysis starting at Figure 4.1 demonstrates the influence of changing the lane addition trigger standards and the funding level on the percentage of roadway miles or VMT of a certain network within each peak hour volume-capacity ratio category. The points on the graphs represent the network roadway condition as a result of 20 years of applying each deficiency standard and each five-year funding level.

Table 4.2 shows the cost of adding lanes to urban road segments. The HERS model differentiates between lanes added at "Normal" and "High" cost. The HPMS

TABLE 4.1
Lane Addition trigger sets (Mobility Deficiency Standards) to trigger lane additions (based on Peak hour volume capacity ratio)

Road Classification	"High" Deficiency Standard	"Medium" Deficiency Standard	"Low" Deficiency Standard
Interstate	0.7	0.8	0.9
Expressway/Freeway	0.7	0.8	0.9
Principal Arterial	0.75	0.85	0.95
Minor Arterial	0.85	0.9	0.95
Collectors	0.95	0.97	1

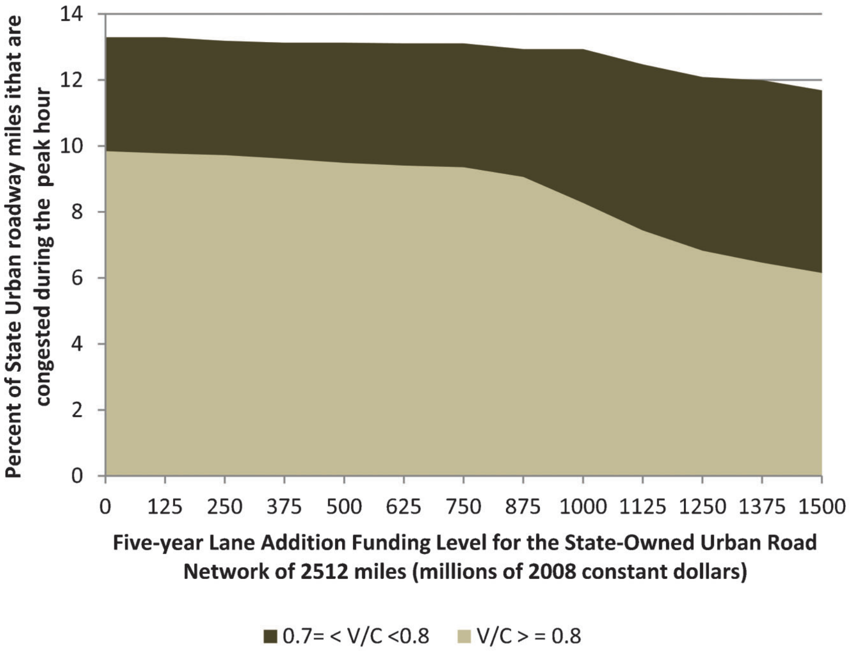


Figure 4.1 Percent of State Urban road miles congested during the peak hour in 2029 under the Low Deficiency Standard for triggering lane additions.

dataset contains a Widening Feasibility indicator (WDFEAS) for each road section to provide information on how many lanes can be added to a certain road section at a normal cost. This state-supplied indicator reflects the presence of physical features along the section that would increase the cost of adding lanes such as the presence of severe terrain, cemeteries and park land. As more lanes are added to a certain section, the HERS-ST software reduces the WDFEAS value for that section until the addition of lanes can no longer be done at a normal cost and must be done at a high cost. For each road section, the addition of lanes can continue to occur at a high cost up to the MAXLANES parameter setting contained in HERS-ST, which was set at 20 lanes for this set of analyses.

Tables 4.3 and 4.4 show the initial VMT (2009) and final VMT (2029) on the State Urban and Federal-Aid Urban roads, respectively, as contained in the HPMS 2009 Indiana data file.

4.3 Mobility Analysis Results for the State-Owned Urban Roadway Network

4.3.1 Peak-Hour Mobility Condition of State Urban Roads in 2029 due to Application of the Low Deficiency Standard for Triggering Lane Additions During the 2009–2029 Period

Tables 4.5 and 4.6 show the peak hour mobility condition for the State-Owned Urban road network, as well as for its primary components: the Urban Interstate and Expressways and the Other State-Owned Urban Arterials.

Application of the Low Deficiency Standard in triggering lane additions for the State-Owned Urban road network results in:

- No effect on the percent of State Urban roadway miles or VMT experiencing a peak hour V/C of 0.7 or more.

TABLE 4.2
Cost of adding lanes to Urban Roads (thousands of 2008 constantdollars per lane mile)

		Normal Cost	High Cost
Interstates/Expressways	Small Urban (population of 5,000 to 49,999)	3540	5841
	Small Urbanized (population of 50,000 to 199,999)	3868	6382
	Large Urbanized (population of 200,000 or more)	8065	13307
Principal Arterials	Small Urban (population of 5,000 to 49,999)	3009	4965
	Small Urbanized (population of 50,000 to 199,999)	3260	5379
	Large Urbanized (population of 200,000 or more)	4771	7872
Arterials/Collectors	Small Urban (population of 5,000 to 49,999)	2222	3666
	Small Urbanized (population of 50,000 to 199,999)	2342	3864
	Large Urbanized (population of 200,000 or more)	3246	5356

TABLE 4.3
Initial (2009) and Final (2029) VMT of the State Urban Roads

	Interstates and Expressways	Other Arterials	Major Collectors	Total
Initial (2009) VMT of Indiana's State Urban Highway Network (in millions)	10803	8762	40	19605
Final (2029) VMT of Indiana's State Urban Highway Network (in millions)	15988	9831	45	25864

TABLE 4.4
Initial (2009) and Final (2029) VMT of the Federal-Aid Urban Roads

	Interstates and Expressways	Other Arterials	Major Collectors	Total
Initial (2009) VMT of Indiana's Federal-Aid Urban Network (in millions)	10971	18233	6087	35291
Final (2029) VMT of Indiana's Federal-Aid Urban Network (in millions)	16236	20457	6829	43522

- Between the five-year funding levels of $875 million and $1500 million, the percent of State Urban roadway miles with a peak hour V/C of at least 0.8 decreasing from 9.1% to 6.2% as Table 4.5 (Column 2) and Figure 4.1 show, and
- The percent of State Urban VMT experiencing a peak hour V/C of at least 0.8 decreasing from 33.0% to 22.0%, as Table 4.6 (Column 2) and Figure 4.3 show.
- The Urban Interstate and Expressway subset demonstrating a pattern similar to the entire system; however, there is a very slight decrease in the percent of roadway miles or VMT facing congestion during the peak hour ($V/C \geq 0.7$) in response to increased funding, as Figures 4.2 and 4.4 show.
- Between the five-year funding levels of $875 million and $1500 million, the percent of Urban Interstate and Expressway roadway miles that are subjected to peak hour V/C of at least 0.8 decreasing from 25.8% to 16.7% as Table 4.5 (Column 4) shows, and
- The percent of Urban Interstate and Expressway VMT that are subjected to peak hour V/C of at least 0.8 decreasing from 48.4% to 31.5% as Table 4.6 (Column 4) shows.

Important Analysis Observation:

- Overall, this case shows that if lane addition is deployed as the only strategy to address future peak hour congestion issues, the Low Deficiency Standard for triggering lane additions would not be sufficient to meaningfully improve peak hour mobility for the State Urban road network.

TABLE 4.5
Peak hour Mobility Condition of State Urban roads in 2029 (by percent of uncongested and congested miles) with different funding levels under the Low Deficiency Standard for triggering lane additions during the 2009–2029 period

Five-year Lane Addition Funding Level for the State-Owned Urban System (millions of 2008 constant dollars)	(1) Percent of State-Owned Urban roadway miles with peak hour $V/C < 0.7$	(2) Percent of State-Owned Urban roadway miles with peak hour $V/C \geq 0.8$	(3) Percent of Urban Interstate and Expressway miles with peak hour $V/C < 0.7$	(4) Percent of Urban Interstate and Expressway miles with peak hour $V/C \geq 0.8$	(5) Percent of Other State-Owned Urban Arterial roadway miles with peak hour $V/C < 0.7$	(6) Percent of Other State-Owned Urban Arterial roadway miles with peak hour $V/C \geq 0.8$
0	86.7	9.8	65.1	28.6	94.0	3.9
125	86.7	9.8	65.1	28.3	94.0	3.9
250	86.8	9.7	65.1	28.1	94.2	3.9
375	86.9	9.6	65.2	27.7	94.2	3.9
500	86.9	9.5	65.2	27.1	94.2	3.9
625	86.9	9.4	65.2	26.8	94.2	3.9
750	86.9	9.4	65.2	26.6	94.2	3.9
875	87.1	9.1	65.9	25.8	94.2	3.7
1000	87.1	8.3	65.9	22.9	94.2	3.6
1125	87.5	7.4	67.8	19.5	94.2	3.6
1250	87.9	6.8	68.2	18.4	94.6	3.1
1375	88.0	6.5	68.6	17.6	94.6	2.9
1500	88.3	6.2	69.5	16.7	94.7	2.8

TABLE 4.6
Peak hour Mobility Condition of State Urban roads in 2029 (by percent VMT facing uncongested and congested travel) with different funding levels under the Low Deficiency Standard for triggering lane additions during the 2009–2029 period

Five-year Lane Addition Funding Level for the State-Owned Urban System (millions of 2008 constant dollars)	(1) Percent of State-Owned Urban VMT facing V/C < 0.7 during peak hour travel	(2) Percent of State-Owned Urban VMT facing V/C ≥ 0.8 during peak hour travel	(3) Percent of Urban Interstate and Expressway VMT facing V/C < 0.7 during peak hour travel	(4) Percent of Urban Interstate and Expressway VMT facing V/C ≥ 0.8 during peak hour travel	(5) Percent of Other State-Owned Urban Arterial VMT facing V/C < 0.7 during peak hour travel	(6) Percent of Other State-Owned Urban Arterial VMT facing V/C ≥ 0.8 during peak hour travel
0	58.3	34.6	40.1	50.7	87.8	8.5
125	58.3	34.5	40.1	50.5	87.8	8.5
250	58.6	34.4	40.4	50.5	88.0	8.5
375	58.7	34.2	40.7	50.1	88.1	8.5
500	58.8	34.2	40.8	50.0	88.1	8.5
625	58.9	34.1	40.9	50.0	88.1	8.5
750	58.9	33.2	41.0	48.5	88.1	8.5
875	59.1	33.0	41.2	48.4	88.1	8.3
1000	59.2	28.6	41.4	41.3	88.1	8.0
1125	60.7	24.3	43.8	34.4	88.1	8.0
1250	61.2	23.2	44.3	33.2	88.6	7.2
1375	61.4	22.4	44.6	32.1	88.6	6.8
1500	61.8	22.0	45.3	31.5	88.7	6.7

4.3.2 Peak-Hour Mobility Condition of State Urban Roads in 2029 due to Application of the Medium Deficiency Standard for Triggering Lane Additions in the 2009–2029 Period

Application of the Medium Deficiency Standard in triggering lane additions for the State-Owned Urban road network results in:

- Only a slight decrease in the percent of State Urban roadway miles congested during the peak hour (V/C ≥0.7), as Table 4.7 and Figure 4.5 show.
- Between the five-year funding levels of $750 million and $1875 million, the percent of State Urban VMT facing peak hour congestion decreasing from 40.6% to 25.4%, as Table 4.8 and Figure 4.7 show.
- Between the five-year funding levels of $750 million and $1875 million, the percent of Urban Interstate and Expressway miles congested during the peak hour (V/C ≥0.7) decreasing from 33.7% to 19.0% as Figure 4.6 shows.
- Between the five-year funding levels of $750 million and $1875 million, the percent of Urban Interstate and Expressway VMT facing congestion during the peak hour decreasing from 58.1% to 36.0%, as Figure 4.8 shows.

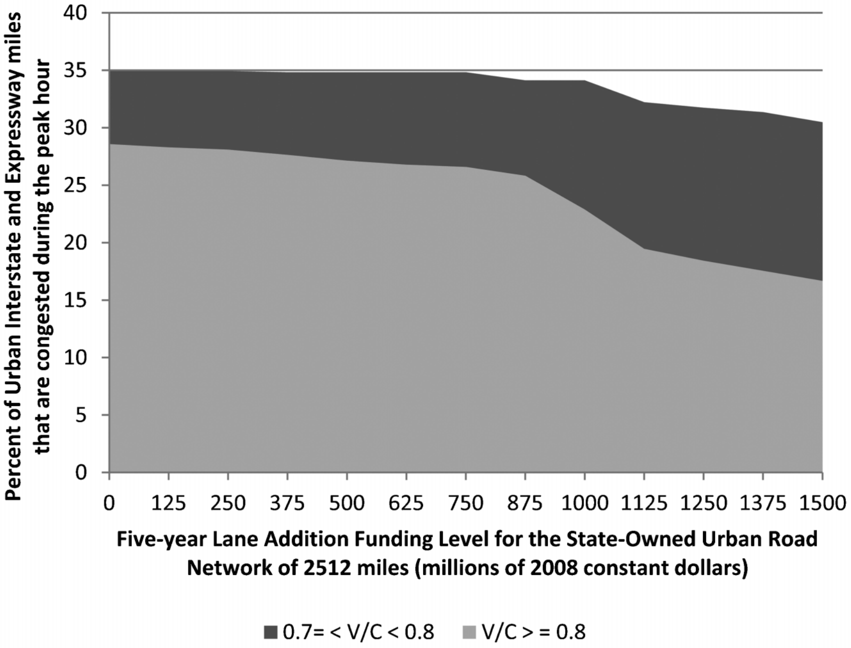


Figure 4.2 Percent of Urban Interstate and Expressway miles congested during the peak hour in 2029 under the Low Deficiency Standard for triggering lane additions.

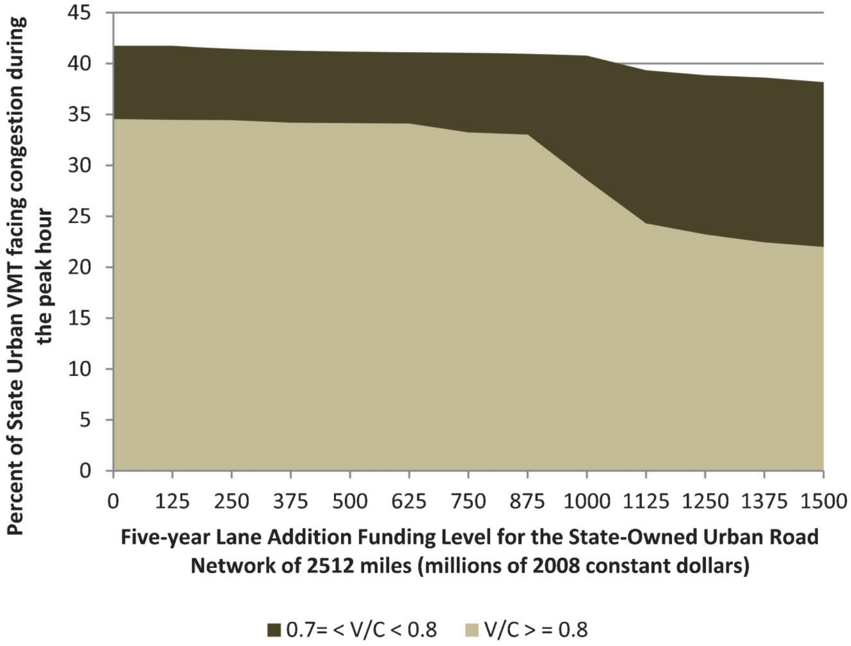


Figure 4.3 Percent of State Urban VMT facing congestion during the peak hour in 2029 under the Low Deficiency Standard for triggering lane additions.

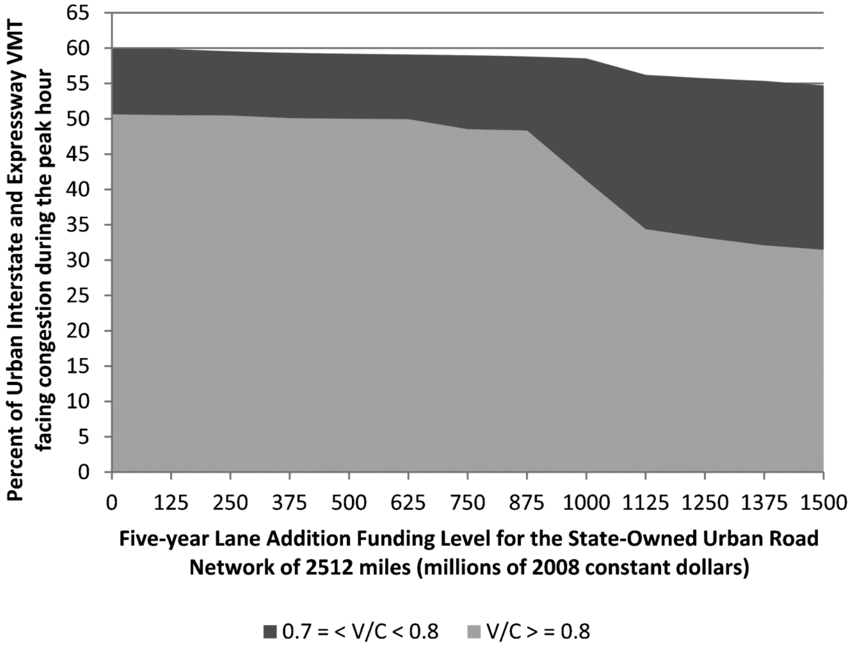


Figure 4.4 Percent of Urban Interstate and Expressway VMT facing congestion during the peak hour in 2029 under the low deficiency dtandard for triggering lane additions.

TABLE 4.7

Peak hour Mobility Condition of State Urban roads in 2029 (by percent of uncongested and congested miles) with different funding levels under the Medium Deficiency Standard for triggering lane additions during the 2009–2029 period

Five-year Lane Addition Funding Level for the State-Owned Urban System (millions of 2008 constant dollars)	(1) Percent of State-Owned Urban roadway miles with peak hour $V/C < 0.7$	(2) Percent of State-Owned Urban roadway miles with peak hour $V/C \geq 0.8$	(3) Percent of Urban Interstate and Expressway miles with peak hour $V/C < 0.7$	(4) Percent of Urban Interstate and Expressway miles with peak hour $V/C \geq 0.8$	(5) Percent of Other State-Owned Urban Arterial roadway miles with peak hour $V/C < 0.7$	(6) Percent of Other State-Owned Urban Arterial roadway miles with peak hour $V/C \geq 0.8$
0	86.7	9.8	65.1	28.6	94.0	3.9
125	86.7	9.7	65.1	28.1	94.0	3.9
250	86.7	9.7	65.1	28.1	94.0	3.9
375	86.7	9.6	65.1	27.4	94.0	3.9
500	86.7	9.5	65.2	27.3	94.0	3.9
625	86.8	9.2	65.4	26.0	94.0	3.9
750	87.0	8.8	66.3	24.4	94.0	3.8
875	87.7	7.7	68.5	20.6	94.2	3.6
1000	87.7	7.3	68.5	19.2	94.2	3.5
1125	88.2	6.3	69.0	17.3	94.7	2.8
1250	89.1	5.2	72.8	12.8	94.7	2.8
1375	89.7	4.5	74.5	10.9	95.0	2.5
1500	90.5	3.8	77.2	8.4	95.1	2.3
1625	90.8	3.2	78.1	7.3	95.3	1.9
1750	91.2	2.9	78.6	6.7	95.6	1.7
1875	92.1	2.0	81.0	4.4	96.0	1.2

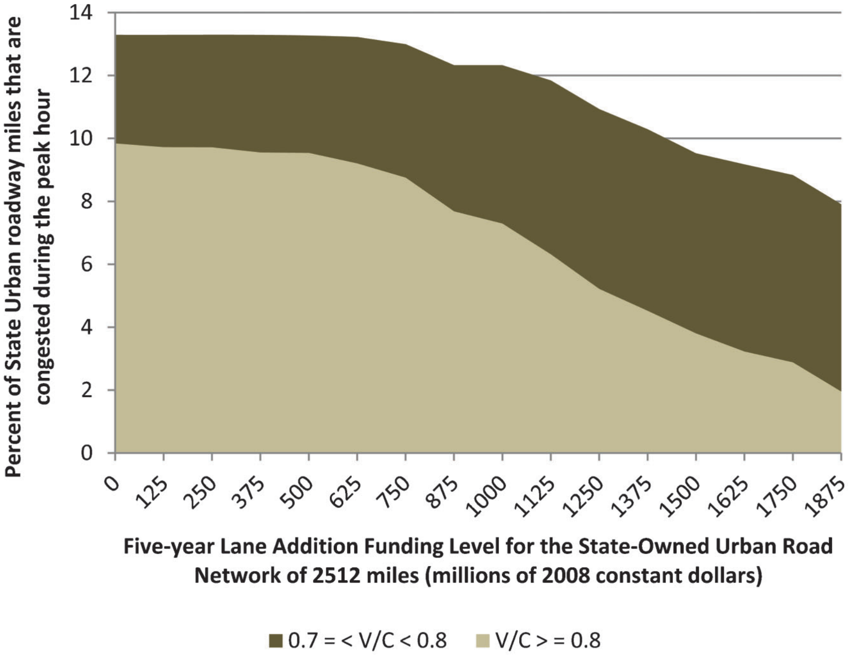


Figure 4.5 Percent of State urban road miles congested during the peak hour in 2029 under the Medium Deficiency Standard for triggering lane additions.

TABLE 4.8

Peak hour Mobility Condition of State Urban roads in 2029 (by percent VMT facing uncongested and congested travel) with different funding levels under the Medium Deficiency Standard for triggering lane additions during the 2009–2029 period

Five-year Lane Addition Funding Level for the State-Owned Urban System (millions of 2008 constant dollars)	(1) Percent of State-Owned Urban VMT facing V/C < 0.7 during peak hour travel	(2) Percent of State-Owned Urban VMT facing V/C ≥ 0.8 during peak hour travel	(3) Percent of Urban Interstate and Expressway VMT facing V/C < 0.7 during peak hour travel	(4) Percent of Urban Interstate and Expressway VMT facing V/C ≥ 0.8 during peak hour travel	(5) Percent of Other State-Owned Urban Arterial VMT facing V/C < 0.7 during peak hour travel	(6) Percent of Other State-Owned Urban Arterial VMT facing V/C ≥ 0.8 during peak hour travel
0	58.3	34.6	40.1	50.7	87.8	8.5
125	58.6	34.3	40.6	50.3	87.8	8.5
250	58.7	34.2	40.8	50.2	87.8	8.5
375	58.8	34.1	40.9	49.9	87.8	8.5
500	59.0	33.7	41.2	49.2	87.8	8.5
625	59.2	32.9	41.6	47.9	87.8	8.5
750	59.4	31.4	41.9	45.7	87.8	8.1
875	61.4	26.7	44.9	38.5	88.3	7.6
1000	61.6	24.4	45.1	34.8	88.3	7.4
1125	62.4	21.0	45.7	30.8	89.7	5.3
1250	66.2	16.0	51.7	22.8	89.7	5.2
1375	68.1	13.9	54.6	19.6	90.1	4.8
1500	71.2	11.3	59.4	15.8	90.5	4.2
1625	72.4	9.8	61.2	13.6	90.7	3.6
1750	72.9	9.3	61.7	13.1	91.1	3.2
1875	74.6	7.6	64.0	10.7	91.7	2.6

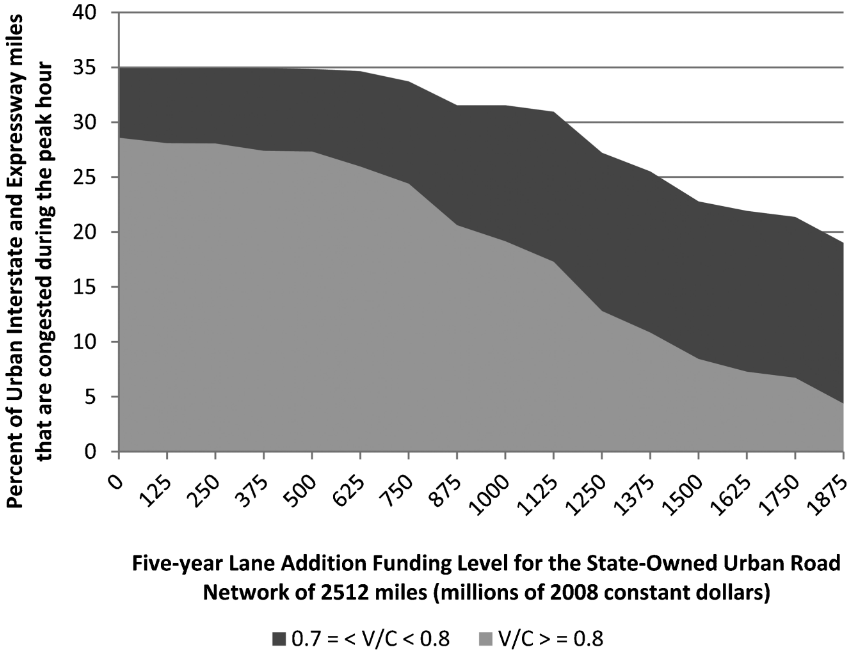


Figure 4.6 Percent of Urban Interstate and Expressway miles congested during the peak hour in 2029 under the Medium Deficiency Standard for triggering lane additions.

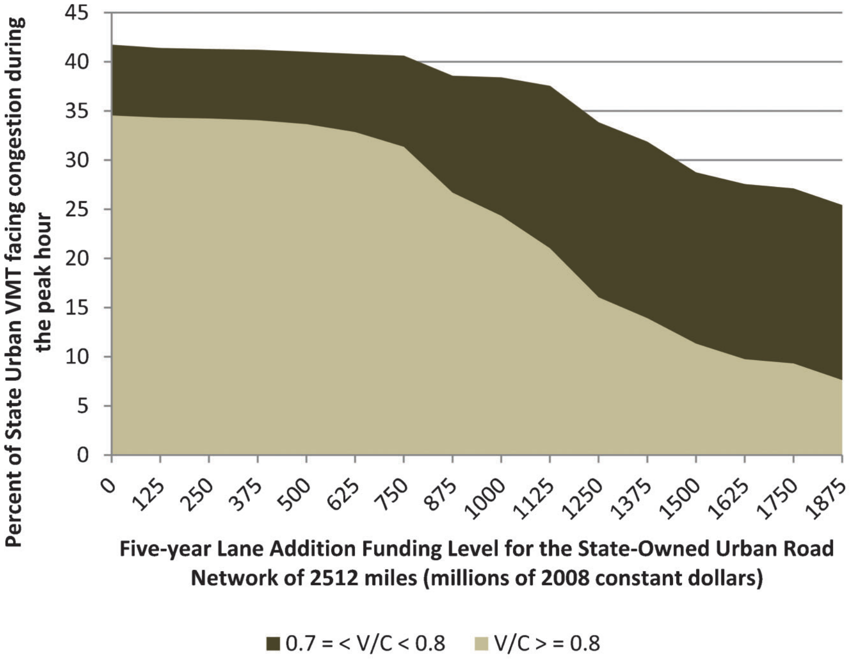


Figure 4.7 Percent of State urban VMT facing congestion during the peak hour in 2029 under the Medium Deficiency Standard for triggering lane additions.

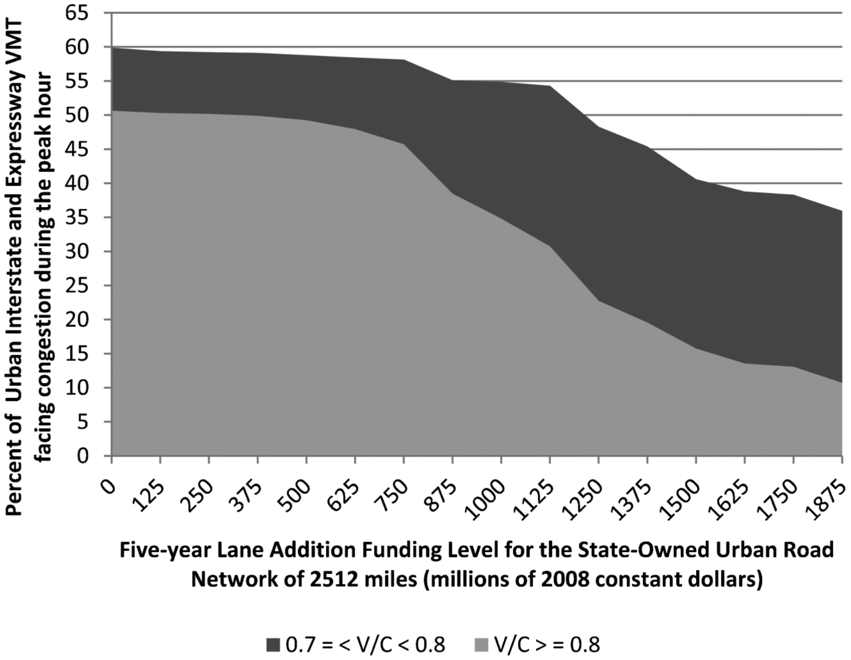


Figure 4.8 Percent of Urban Interstate and Expressway VMT facing congestion during the peak hour in 2029 under the Medium Deficiency Standard for triggering lane additions.

Important Analysis Observation:

- Overall, this case shows that, if lane addition is deployed as the only strategy to address future peak hour congestion issues, the Medium Deficiency Standard for triggering lane additions would address the Urban Interstates and Expressways sections that are most severely congested during the peak hour by percent of miles and by percent of VMT.

4.3.3 Peak-Hour Mobility Condition of State Urban Roads in 2029 due to Application of the High Deficiency Standard for Triggering Lane Additions in the 2009–2029 Period

Application of the High Deficiency Standard in triggering lane additions for the State-Owned Urban road network results in:

- Starting at the five-year funding level of $625 million, a moderate decrease in the percent of State Urban roadway miles where the peak hour V/C is at least 0.7(See Table 4.9 and Figure 4.9).
- Between the five-year funding levels of $625 million and $2500 million, a pronounced decrease in the percent of State Urban VMT facing congestion during the peak hour, with the figure dropping from 39.6% to 10.3%, as Table 4.10 and Figure 4.11 show.
- Between the five-year funding levels of $625 million and $2500 million, the percent of Urban Interstate and Expressway road miles congested during the peak hour decreasing from 32.8% to 4.9% as Figure 4.10 shows, and
- The percent of Urban Interstate and Expressway VMT facing congestion during the peak hour decreasing from 56.7% to 13.4%, which is demonstrated in Figure 4.12.
- For the five-year funding level of $1500 million, the percent of State Urban VMT facing congestion during the peak hour reaching 30.8% as compared to 38.2% for the low standard.

Important Analysis Observations:

- Overall, this case shows that, if lane addition is deployed as the only strategy to address future peak hour congestion issues, the High Deficiency Standard for triggering lane additions would meaningfully reduce the congested sections of Urban Interstates and Expressways.
- However, it is important to note that the High Deficiency Standard entails placing all road sections that experienced congestion ($V/C \geq 0.7$) during the peak hour on the candidate list for receiving a lane addition. Such a strategy is not likely to be implemented.

4.3.4 Summary of the Performance of the Three Deficiency Standards for Triggering Lane Addition in Improving the Peak-Hour Mobility Condition of State Urban Roads

Tables 4.11 and 4.12 summarize how the choice of deficiency standard affects the magnitude by which the peak-hour mobility condition improves in response to a unit increase in funding for lane addition projects on the State Urban road network.

- The “breakpoint” represents the funding level at which the “slope” seen in the previously-shown odd-numbered figures

TABLE 4.9
Peak hour Mobility Condition of State Urban roads in 2029 (by percent of uncongested and congested miles) with different funding levels under the High Deficiency Standard for triggering lane additions during the 2009–2029 period

Five-year Lane Addition Funding Level for the State-Owned Urban System(millions of 2008 constant dollars)	(1) Percent of State-Owned Urban roadway miles with peak hour V/C < 0.7	(2) Percent of State-Owned Urban roadway miles with peak hour V/C ≥ 0.8	(3) Percent of Urban Interstate and Expressway miles with peak hour V/C < 0.7	(4) Percent of Urban Interstate and Expressway miles with peak hour V/C ≥ 0.8	(5) Percent of Other State-Owned Urban Arterial roadway miles with peak hour V/C < 0.7	(6) Percent of Other State-Owned Urban Arterial roadway miles with peak hour V/C ≥ 0.8
0	86.7	9.8	65.1	28.6	94.0	3.9
125	86.9	9.7	65.1	27.9	94.2	3.9
250	87.0	9.5	65.8	27.3	94.2	3.9
375	87.0	9.3	65.8	26.3	94.2	3.9
500	87.3	9.1	66.6	25.7	94.2	3.9
625	87.4	9.0	67.2	25.1	94.2	3.9
750	87.6	8.4	67.8	22.9	94.3	3.7
875	87.9	8.0	68.8	21.6	94.3	3.7
1000	88.3	7.6	70.7	20.3	94.4	3.5
1125	88.7	6.8	72.0	18.0	94.4	3.3
1250	89.1	6.2	73.7	15.4	94.4	3.3
1375	89.5	5.5	74.5	13.6	94.6	3.0
1500	89.9	4.7	75.8	11.2	94.8	2.6
1625	90.5	4.0	77.4	9.6	95.1	2.2
1750	91.6	3.0	80.1	7.6	95.6	1.6
1875	91.8	2.8	80.9	6.8	95.6	1.6
2000	92.7	2.5	84.2	5.9	95.9	1.4
2125	93.5	1.6	86.9	2.9	96.0	1.2
2250	94.3	1.5	89.1	2.9	96.3	1.0
2375	95.1	1.0	90.7	2.7	97.0	0.4
2500	96.5	0.8	95.1	2.7	97.3	0.1

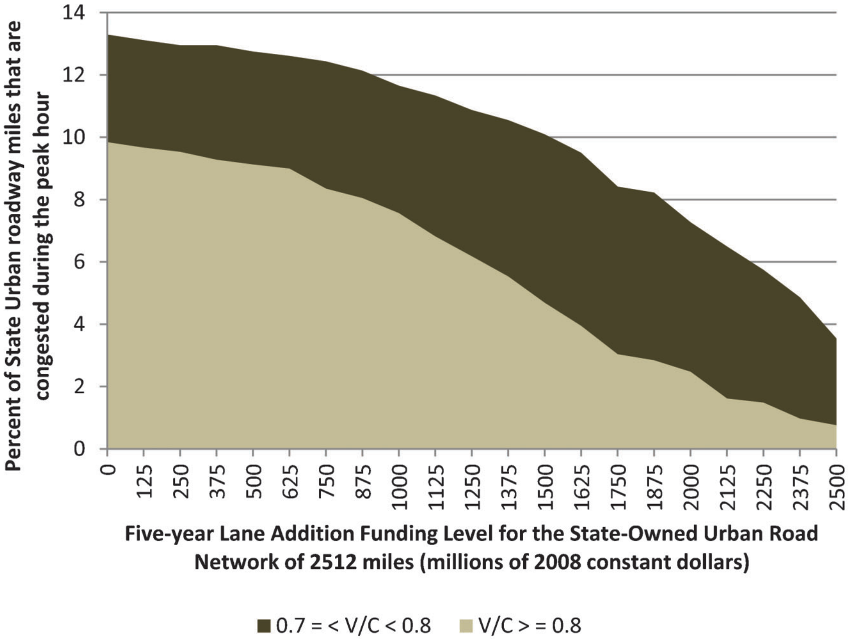


Figure 4.9 Percent of State Urban road miles congested during the peak hour in 2029 under the High Deficiency Standard for triggering lane additions.

TABLE 4.10
Peak hour Mobility Condition of State Urban roads in 2029 (by percent VMT facing uncongested and congested travel) with different funding levels under the High Deficiency Standard for triggering lane additions during the 2009–2029 period

Five-year Lane Addition Funding Level for the State-Owned Urban System (millions of 2008 constant dollars)	(1) Percent of State-Owned Urban VMT facing V/C < 0.7 during peak hour travel	(2) Percent of State-Owned Urban VMT facing V/C ≥ 0.8 during peak hour travel	(3) Percent of Urban Interstate and Expressway VMT facing V/C < 0.7 during peak hour travel	(4) Percent of Urban Interstate and Expressway VMT facing V/C ≥ 0.8 during peak hour travel	(5) Percent of Other State-Owned Urban Arterial VMT facing V/C < 0.7 during peak hour travel	(6) Percent of Other State-Owned Urban Arterial VMT facing V/C ≥ 0.8 during peak hour travel
0	58.3	34.6	40.1	50.7	87.8	8.5
125	59.4	33.9	41.8	49.6	88.1	8.4
250	59.9	33.5	42.5	49.1	88.2	8.4
375	60.1	32.6	42.8	47.5	88.2	8.4
500	60.3	32.5	43.1	47.4	88.2	8.4
625	60.4	32.3	43.3	47.0	88.2	8.4
750	61.1	30.2	44.1	44.0	88.6	8.0
875	61.6	29.4	44.9	42.7	88.7	7.9
1000	63.5	28.0	48.0	40.9	88.8	7.1
1125	64.9	24.6	50.2	35.7	88.9	6.5
1250	66.9	21.4	53.2	30.7	89.2	6.5
1375	67.8	18.9	54.3	27.1	89.6	5.7
1500	69.2	14.8	56.2	21.2	90.2	4.6
1625	70.7	13.2	58.4	19.0	90.7	3.7
1750	74.2	10.2	63.4	14.8	91.6	2.7
1875	75.2	9.1	65.1	13.1	91.6	2.7
2000	79.6	8.4	71.8	12.3	92.3	2.1
2125	81.6	6.2	74.9	8.8	92.4	1.9
2250	84.7	6.0	79.5	8.8	93.1	1.6
2375	86.8	5.5	82.1	8.6	94.6	0.4
2500	89.7	5.4	86.6	8.6	94.9	0.1

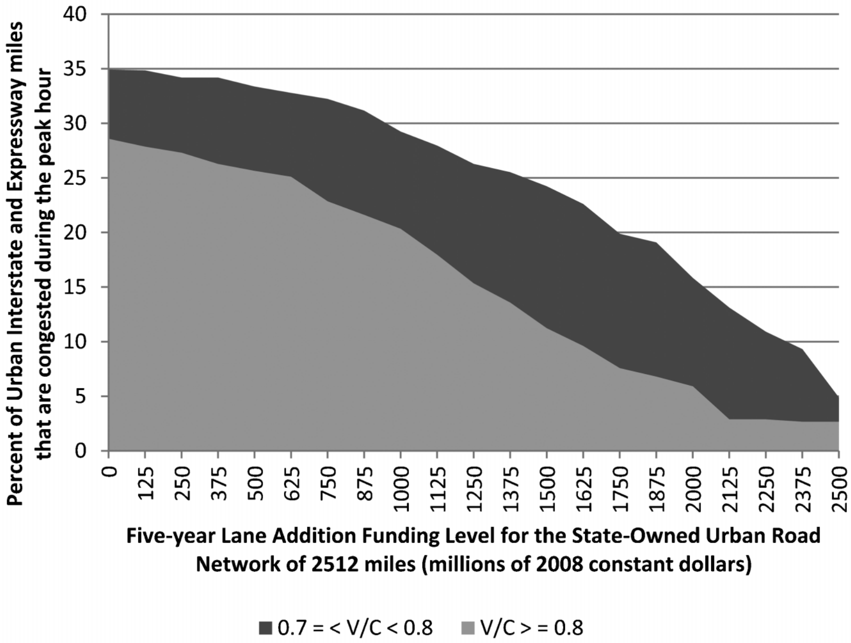


Figure 4.10 Percent of Urban Interstate and Expressway miles congested during the peak hour in 2029 under the High Deficiency Standard for triggering lane additions.

changes notably. The presence of breakpoints shows that, for all the tested lane addition trigger standards, the unit increase in funding corresponds to a different magnitude of improvement in the mobility condition at different funding ranges.

- Comparison of the "breakpoints" and subsequent "slopes" across deficiency standards is difficult, because each deficiency standard results in breakpoints at different funding levels.
- Furthermore, the Low Deficiency Standard has been shown to have a different breakpoint for each of the peak hour mobility condition categories of V/C<0.7 and V/C ≥0.8.
- Tables 4.11 and 4.12 are shown to quantify the "slopes" shown in the odd-numbered figures 4.1–4.11. Additionally, these tables are useful in examining the performance of each lane addition trigger standard in reducing peak hour congestion of the State Urban roads. This task can be

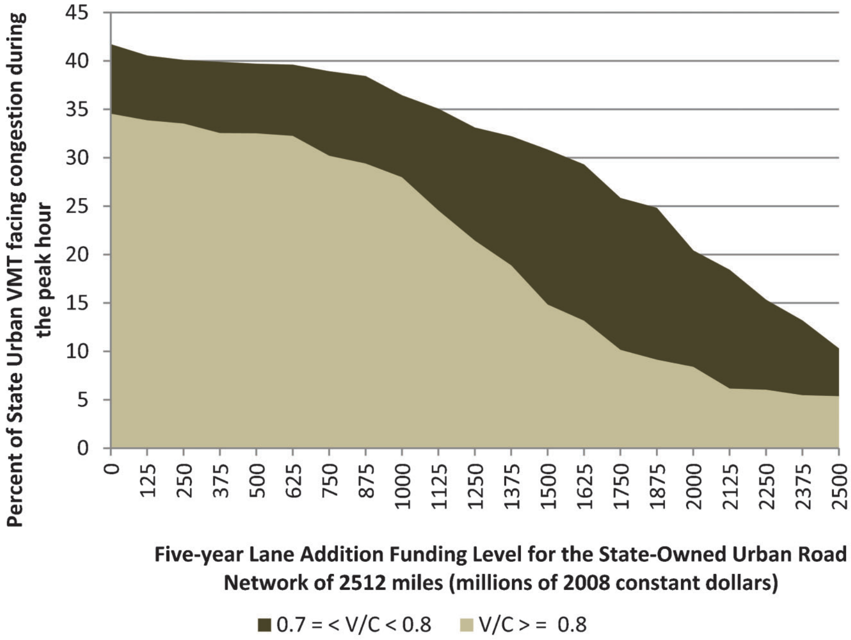


Figure 4.11 Percent of State Urban VMT facing congestion during the peak hour in 2029 under the High Deficiency Standard for triggering lane additions.

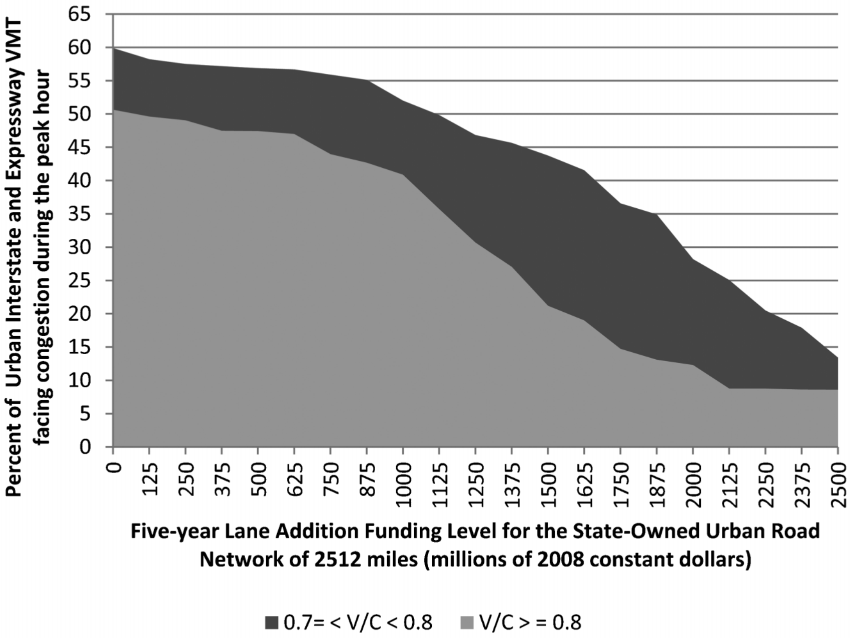


Figure 4.12 Percent of Urban Interstate and Expressway VMT facing congestion in 2029 during the peak hour under the High Deficiency Standard for triggering lane additions.

accomplished by looking at the peak hour mobility condition for different funding amounts.

- For example, Tables 4.11 and 4.12 show that the Medium Deficiency Standard has more cost-efficient performance than the Low Deficiency Standard at all funding levels in reducing the percent of State Urban road miles or VMT facing peak hour congestion.
- Although, the High Deficiency Standard shows more cost-efficient performance than the Low Deficiency Standard at all funding amounts, the High Deficiency Standard does not seem to be more cost-efficient than the Medium Deficiency Standard at the five-year funding levels of $1500 million and $1875 million.

4.4 Mobility Analysis Results for the Federal-Aid Urban Roadway Network

4.4.1 Peak-Hour Mobility Condition of Federal-Aid Urban Roads in 2029 due to Application of the Low Deficiency Standard for Triggering Lane Additions During the 2009–2029 Period

Tables 4.13 and 4.14 show the peak hour mobility condition for the entire Federal-Aid Urban road network, as well as for two alternative component break downs: the Urban Arterial/Urban Major Collector network components and the State-Owned/Non State-Owned components.

Application of the Low Deficiency Standard in triggering lane additions for the Federal-Aid Urban road network results in:

- A very small decrease in the percent of Federal-Aid Urban roadway miles where peak hour travel is congested ($V/C \geq 0.7$).
- Between the five-year funding levels of $1250 and $2500 million, the percent of Federal-Aid Urban roadway miles with peak hour V/C of at least 0.8 dropping from 13.9% to 9.9%, as shown in Table 4.13 (Column 2) and Figure 4.13.
- Between the five-year funding levels of $0 and $2500 million, the percent of Federal-Aid Urban VMT facing peak hour V/C of at least 0.8 demonstrating a steady decline from 30.9% to 16.6%, as shown in Table 4.14 (Column 2) and Figure 4.14.

Important Analysis Observation:

- This case illustrates that, although there is not a substantial percent of Federal-Aid Urban road miles on which peak hour congestion occurs, the percent of VMT that face peak hour congestion when traveling is worthy of attention.

4.4.2 Peak-Hour Mobility Condition of Federal-Aid Urban Roads in 2029 due to Application of the Medium Deficiency Standard for Triggering Lane Additions During the 2009–2029 Period

Application of the Medium Deficiency Standard in triggering lane additions for the Federal-Aid Urban road network results in:

- A very small decrease in the percent of Federal-Aid Urban roadway miles where peak hour travel is congested ($V/C \geq 0.7$), as shown by Table 4.15 and Figure 4.15.

TABLE 4.11

Summary of the performance of the three deficiency standards for triggering lane addition in improving the peak-hour mobility condition of State Urban roads, by percent miles, in 2029

		Value at No Funding for lane addition projects	Unit change in Value from No Funding to Break-point 1 funding (per $100 million increase in five-year funding level)	Break-point 1 funding level (millions of 2008 constant dollars per five years)	Value at Break-point 1 funding level	Unit change in Value from Break-point 1 funding to Break-point 2 funding (per $100 million increase in five-year funding level)	Break-point 2 funding level (millions of 2008 constant dollars per five years)	Value at Break-point 2 funding level	Unit change in Value beyond the Break-point 2 funding level (per $100 million increase in five-year funding level)	Value at funding level of $1500 million per five years	Value at funding level of $1875 million per five years	Value at funding level of $2500 million per five years
Low												
Percent of road miles within a certain peak hour congestion category	V/C <0.7	86.7	0.04	1000	87.1	0.24				88.3		
	V/C ≥ 0.8	9.8	−0.08	875	9.1	−0.46				6.2		
Medium												
Percent of road miles within a certain peak hour congestion category	V/C <0.7	86.7	0.04	750	87.0	0.45				90.5	92.1	
	V/C ≥ 0.8	9.8	−0.13	750	8.8	−0.60				3.8	2.0	
High												
Percent of road miles within a certain peak hour congestion category	V/C <0.7	86.7	0.11	625	87.4	0.49				89.9	91.8	96.5
	V/C ≥ 0.8	9.8	−0.13	625	9.0	−0.53	1750	3.0	−0.29	4.7	2.8	0.8

TABLE 4.12

Summary of the performance of the three deficiency standards for triggering lane addition in improving the peak-hour mobility condition of State Urban roads, by percentVMT, in 2029

		Value at No Funding for lane addition projects	Unit change in Value from No Funding to Break-point 1 funding (per $100 million increase in five-year funding level)	Break-point 1 funding level (millions of 2008 constant dollars per five years)	Value at Break-point 1 funding level	Unit change in Value from Break-point 1 funding to Break-point 2 funding (per $100 million increase in five-year funding level)	Break-point 2 funding level (millions of 2008 constant dollars per five years)	Value at Break-point 2 funding level	Unit change in Value beyond the Break-point 2 funding level (per $100 million increase in five-year funding level)	Value at funding level of $1500 million per five years	Value at funding level of $1875 million per five years	Value at funding level of $2500 million per five years
Low												
Percent of VMT traveling on roads experiencing a certain peak hour congestion level	V/C <0.7	58.3	0.09	1000	59.2	0.52				61.8		
	V/C ≥0.8	34.6	−0.18	875	33.0	−3.48	1125	24.3	−0.61	22.0		
Medium												
Percent of VMT traveling on roads experiencing a certain peak hour congestion level	V/C <0.7	58.3	0.15	750	59.4	1.39	1375	68.1	1.3	71.2	74.6	
	V/C ≥0.8	34.6	−0.43	750	31.4	−2.8	1375	13.9	−1.26	11.3	7.6	
High												
Percent of VMT traveling on roads experiencing a certain peak hour congestion level	V/C <0.7	58.3	0.34	625	60.4	1.01	1500	69.2	2.05	69.2	75.2	89.7
	V/C ≥0.8	34.6	−0.37	625	32.3	−1.74	2125	6.2	−0.21	14.8	9.1	5.4

TABLE 4.13

Peak hour Mobility Condition of Federal-Aid Urban roads in 2029 (by percent of uncongested and congested miles) with different funding levels under the Low Deficiency Standard for triggering lane additions during the 2009–2029 period

Five-year Lane Addition Funding Level for the Federal-Aid Urban System (millions of 2008 constant dollars)	(1) Percent of Federal-Aid Urban roadway miles with peak hour V/C < 0.7	(2) Percent of Federal-Aid Urban roadway miles with peak hour V/C ≥ 0.8	(3) Percent of Federal-Aid Urban Arterial miles with peak hour V/C < 0.7	(4) Percent of Federal-Aid Urban Arterial miles with peak hour V/C ≥ 0.8	(5) Percent of Urban Major Collector miles with peak hour V/C < 0.7	(6) Percent of Urban Major Collector miles with peak hour V/C ≥ 0.8	(7) Percent of State-Owned miles with peak hour V/C < 0.7	(8) Percent of State-Owned miles with peak hour V/C ≥ 0.8	(9) Percent of Non-State-Owned miles with peak hour V/C < 0.7	(10) Percent of Non-State-Owned miles with peak hour V/C ≥ 0.8
0	80.4	15.1	82.2	12.1	77.2	20.4	89	8.3	76.9	17.9
250	80.5	14.8	82.5	11.6	77.2	20.4	89.1	7.8	77.0	17.7
500	80.6	14.5	82.5	11.1	77.2	20.4	89.2	7.1	77.1	17.5
750	80.7	14.3	82.7	10.8	77.3	20.3	89.3	6.7	77.2	17.4
1000	80.7	14.2	82.7	10.7	77.3	20.3	89.3	6.6	77.2	17.3
1250	80.7	13.9	82.7	10.3	77.3	20.2	89.3	6.1	77.2	17.1
1500	81.6	13.0	82.9	10.1	79.3	18.1	89.4	6.1	78.4	15.8
1750	81.9	12.2	83.1	9.5	79.8	17.0	89.4	6.0	78.8	14.7
2000	82.7	11.4	83.4	9.1	81.3	15.2	89.5	6.0	79.9	13.6
2250	83.3	10.6	84.4	8.0	81.5	15.0	89.5	5.6	80.8	12.6
2500	84.0	9.9	85.1	7.3	82.1	14.5	89.7	5.5	81.7	11.7

TABLE 4.14

Peak hour Mobility Condition of Federal-Aid Urban roads in 2029 (by percent VMT facing uncongested and congested travel) with different funding levels under the Low Deficiency Standard for triggering lane additions during the 2009–2029 period

Five-year Lane Addition Funding Level for the Federal-Aid Urban System (millions of 2008 constant dollars)	(1) Percent of Federal-Aid Urban VMT facing V/C < 0.7 during peak hour travel	(2) Percent of Federal-Aid Urban VMT facing V/C ≥ 0.8 during peak hour travel	(3) Percent of Federal-Aid Urban Arterial VMT facing V/C < 0.7 during peak hour travel	(4) Percent of Federal-Aid Urban Arterial VMT facing V/C ≥ 0.8 during peak hour travel	(5) Percent of Urban Major Collector VMT facing V/C < 0.7 during peak hour travel	(6) Percent of Urban Major Collector VMT facing V/C ≥ 0.8 during peak hour travel	(7) Percent of State-Owned VMT facing V/C < 0.7 during peak hour travel	(8) Percent of State-Owned VMT facing V/C ≥ 0.8 during peak hour travel	(9) Percent of Non-State-Owned VMT facing V/C < 0.7 during peak hour travel	(10) Percent of Non-State-Owned VMT facing V/C ≥ 0.8 during peak hour travel
0	62.0	30.9	61.8	30.4	63.3	33.7	59.5	31.8	65.7	29.6
250	62.9	29.6	62.9	28.9	63.4	33.6	60.6	29.9	66.3	29.2
500	63.1	27.1	63.0	26.0	63.9	33.2	60.8	25.9	66.5	28.9
750	63.3	25.7	63.1	24.5	64.8	32.4	61.1	23.8	66.6	28.5
1000	63.4	25.6	63.1	24.4	65.2	32.2	61.1	23.7	66.7	28.4
1250	63.6	22.6	63.2	20.8	65.4	32.2	61.1	19.1	67.2	27.8
1500	63.8	22.0	63.3	20.5	66.6	30.3	61.2	19.1	67.6	26.3
1750	64.1	19.3	63.5	17.5	67.2	28.6	61.2	15.7	68.3	24.5
2000	64.4	18.7	63.7	17.2	68.3	26.8	61.4	15.6	68.8	23.2
2250	65.0	17.0	64.4	15.3	68.6	26.3	61.5	13.8	70.2	21.6
2500	65.6	16.6	64.9	14.9	69.2	25.8	61.6	13.8	71.4	20.7

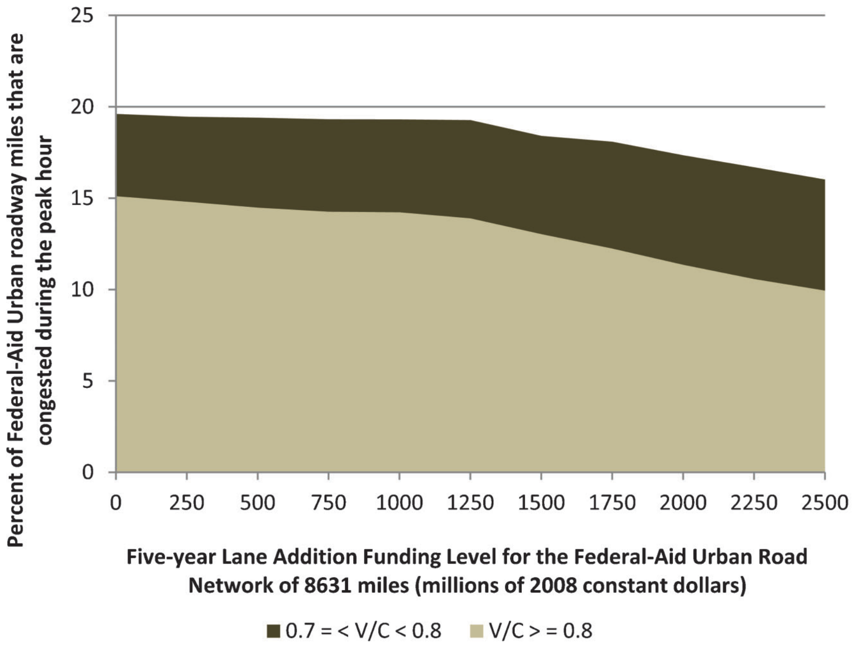


Figure 4.13 Percent of Federal-Aid Urban road miles congested during the peak hour in 2029 under the Low Deficiency Standard for triggering lane additions.

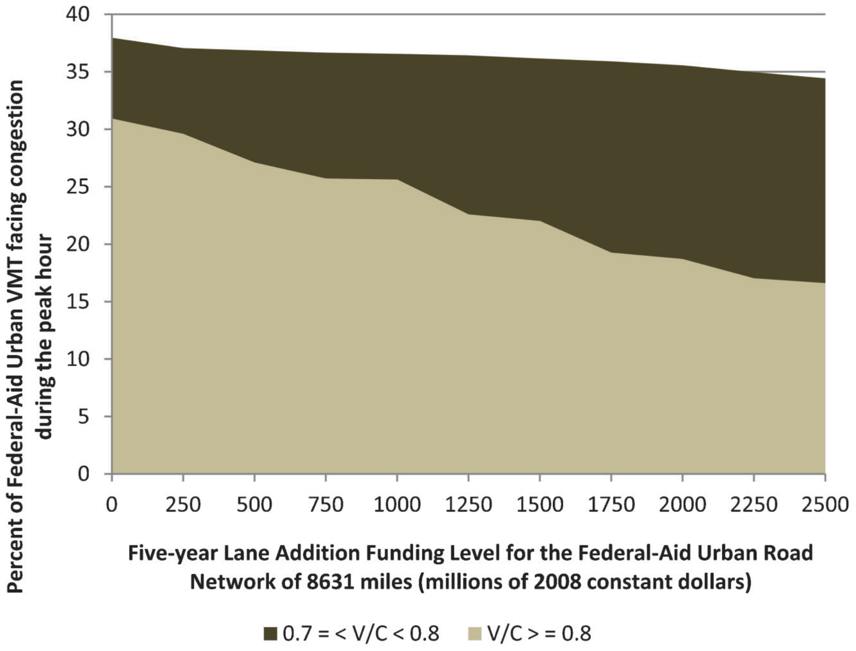


Figure 4.14 Percent of Federal-Aid Urban VMT facing congestion during the peak hour in 2029 under the Low Deficiency Standard for triggering lane additions.

TABLE 4.15
Peak hour Mobility Condition of Federal-Aid Urban roads in 2029 (by percent of uncongested and congested miles) with different funding levels under the Medium Deficiency Standard for triggering lane additions during the 2009–2029 period

Five-year Lane Addition Funding Level for the Federal-Aid Urban System (millions of 2008 constant dollars)	(1) Percent of Federal-Aid Urban roadway miles with peak hour V/C < 0.7	(2) Percent of Federal-Aid Urban roadway miles with peak hour V/C ≥ 0.8	(3) Percent of Federal-Aid Urban Arterial miles with peak hour V/C < 0.7	(4) Percent of Federal-Aid Urban Arterial miles with peak hour V/C ≥ 0.8	(5) Percent of Urban Major Collector miles with peak hour V/C < 0.7	(6) Percent of Urban Major Collector miles with peak hour V/C ≥ 0.8	(7) Percent of State-Owned miles with peak hour V/C < 0.7	(8) Percent of State-Owned miles with peak hour V/C ≥ 0.8	(9) Percent of Non-State-Owned miles with peak hour V/C < 0.7	(10) Percent of Non-State-Owned miles with peak hour V/C ≥ 0.8
0	80.4	15.1	82.2	12.1	77.2	20.4	89	8.3	76.9	17.9
250	80.5	14.7	82.4	11.4	77.2	20.4	89.1	7.6	77.0	17.6
500	80.6	14.4	82.5	11.0	77.2	20.4	89.2	6.8	77.1	17.5
750	80.8	14.0	82.8	10.4	77.3	20.4	89.5	5.8	77.2	17.4
1000	80.8	13.9	82.8	10.2	77.3	20.3	89.6	5.7	77.2	17.3
1250	80.9	13.7	82.9	10.0	77.4	20.2	89.7	5.4	77.3	17.1
1500	81.4	13.1	83.1	9.7	78.4	19.0	90.0	5.1	77.9	16.4
1750	82.0	12.1	83.4	9.2	79.7	17.0	90.1	4.9	78.7	15.0
2000	82.3	11.6	83.7	8.6	79.8	16.7	90.4	4.3	79.0	14.6
2250	83.1	10.7	84.1	8.1	81.4	15.1	90.5	4.2	80.1	13.4
2500	83.8	9.9	85.2	7.0	81.4	15.0	91.0	3.7	80.8	12.5
2750	84.8	9.0	85.8	6.4	83.0	13.5	91.3	3.2	82.1	11.4

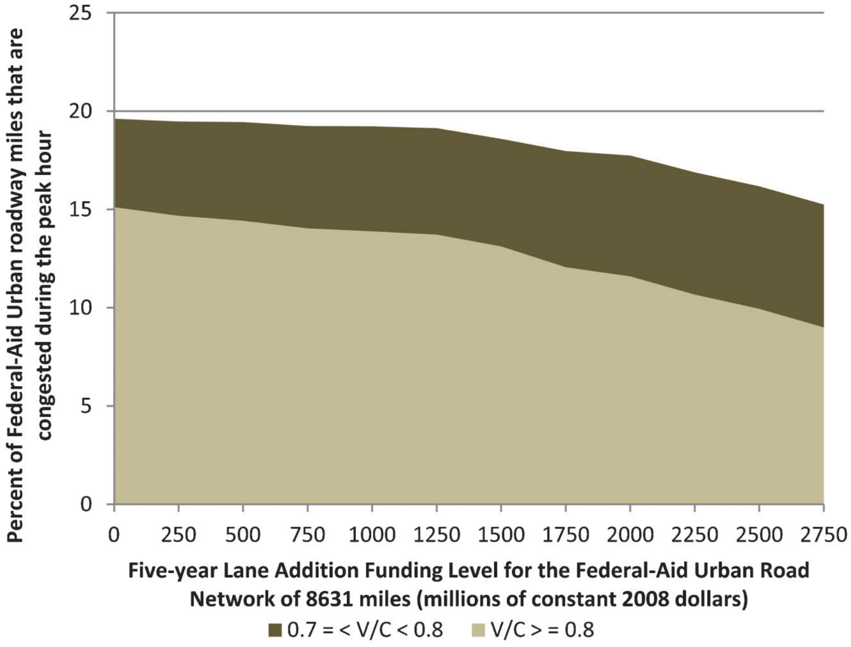


Figure 4.15 Percent of Federal-Aid Urban road miles congested during the peak hour in 2029 under the Medium Deficiency Standard for triggering lane additions.

- Between the five-year funding levels of $1250 and $2500 million, the percent of Federal-Aid Urban roadway miles with peak hour V/C of at least 0.8 dropping from 13.7% to 9.9%, as shown in Table 4.15 (Column 2) and Figure 4.15, and
- As shown in Table 4.16, the percent of Federal-Aid Urban VMT facing peak hour V/C of at least 0.8 dropping from 20.3% to 11.4%, whereas the equivalent figure drops from 22.6% to 16.6% for the Low Deficiency Standard.

Important Analysis Observation

- Only the percent of Federal-Aid Urban VMT facing peak hour V/C of 0.8 or greater is slightly sensitive to the deficiency standard being applied to trigger lane additions.

4.4.3 Peak-Hour Mobility Condition of Federal-Aid Urban Roads in 2029 due to Application of the High Deficiency Standard for Triggering Lane Additions During the 2009–2029 Period

Application of the High Deficiency Standard in triggering lane additions for the Federal-Aid Urban road network results in:

- Compared to the Low Deficiency Standard, no significant decrease in the percent of Federal-Aid Urban roadway miles where peak hour travel is congested ($V/C \geq 0.7$), as shown in Figure 4.17 and Table 4.17.
- Compared to the Medium Standard, no increased effectiveness in reducing the percent of Federal-Aid Urban VMT that faces congestion ($V/C \geq 0.7$) during the peak hour.
- Between the five-year funding levels of $0 and $2500 million, the percent of Federal-Aid Urban VMT facing a peak hour V/C of at least 0.8 dropping from 30.9% to 11.3%, as shown in Table 4.18 (Column 2) and Figure 4.18.

4.4.4 Summary of the Performance of the Three Deficiency Standards for Triggering Lane Addition in Improving the Peak-Hour Mobility Condition of Federal-Aid Urban Roads

Table 4.19 summarizes how the choice of deficiency standard affects the magnitude by which the peak-hour mobility condition improves in response to a unit increase in funding for lane addition projects on the Federal-Aid Urban road network.

- The “breakpoint” represents the funding level at which the “slope” seen in Figures 4.14, 4.16, and 4.18 changes notably. The presence of breakpoints shows that, for all the tested lane addition trigger standards, the unit increase in funding corresponds to a different magnitude of improvement in the mobility condition at different funding ranges.
- Comparison of the “breakpoints” and subsequent “slopes” across deficiency standards is difficult, because each deficiency standard results in breakpoints at different funding levels.
- However, looking at the three right-most columns reveals that at the five-year funding level of $2500 million, the Medium Deficiency Standard has more cost-efficient performance than the Low Deficiency Standard in reducing the percent of Federal-Aid Urban VMT traveling on roads with peak hour congestion.
- The High Deficiency Standard demonstrates nearly the same cost efficiency as the Medium Deficiency Standard in reducing the percent of Federal-Aid Urban VMT traveling on roads with peak hour congestion at the five-year funding levels of $2500 million and $2750 million.

TABLE 4.16

Peak hour Mobility Condition of Federal-Aid Urban roads in 2029 (by percent VMT facing uncongested and congested travel) with different funding levels under the Medium Deficiency Standard for triggering lane additions during the 2009–2029 period

Five-year Lane Addition Funding Level for the Federal-Aid Urban System(millions of 2008 constant dollars)	(1) Percent of Federal-Aid UrbanVMT facingV/C < 0.7 during peak hour travel	(2) Percent of Federal-Aid Urban VMT facingV/C ≥ 0.8 during peak hour travel	(3) Percent of Federal-Aid Urban Arterial VMT facing V/C < 0.7 during peak hour travel	(4) Percent of Federal-Aid Urban Arterial VMT facingV/C ≥ 0.8 during peak hour travel	(5) Percent of Urban Major Collector VMT facing V/C < 0.7 during peak hour travel	(6) Percent of Urban Major Collector VMT facing V/C ≥ 0.8 during peak hour travel	(7) Percent of State-Owned VMT facing V/C < 0.7 during peak hour travel	(8) Percent of State-Owned VMT facing V/C ≥ 0.8 during peak hour travel	(9) Percent of Non-State-Owned VMT facing V/C < 0.7 during peak hour travel	(10) Percent of Non-State-Owned VMT facing V/C ≥ 0.8 during peak hour travel
0	62.0	30.9	61.8	30.4	63.3	33.7	59.5	31.8	65.7	29.6
250	63.1	27.8	62.9	26.8	64.1	33.0	60.6	27.1	66.7	28.9
500	63.5	25.8	63.2	24.6	64.9	32.3	61.3	23.9	66.8	28.6
750	64.1	22.3	63.9	20.5	65.3	32.1	62.2	18.4	66.9	28.1
1000	64.3	21.3	64.1	19.2	65.5	32.1	62.5	16.7	66.9	28.0
1250	64.5	20.3	64.3	18.2	65.5	32.0	62.8	15.3	67.0	27.6
1500	65.2	19.4	65.1	17.2	65.6	31.5	63.8	14.6	67.3	26.4
1750	65.6	18.1	65.4	16.2	67.0	28.6	64.0	14.0	67.9	24.0
2000	66.3	14.3	66.1	11.8	67.3	27.9	65.0	8.2	68.2	23.2
2250	67.2	13.2	66.9	10.7	68.6	26.4	65.3	7.6	70.0	21.4
2500	68.9	11.4	69.0	8.7	68.6	26.2	67.4	5.5	71.0	20.1
2750	69.9	9.7	69.7	7.0	71.1	23.8	68.1	3.6	72.5	18.7

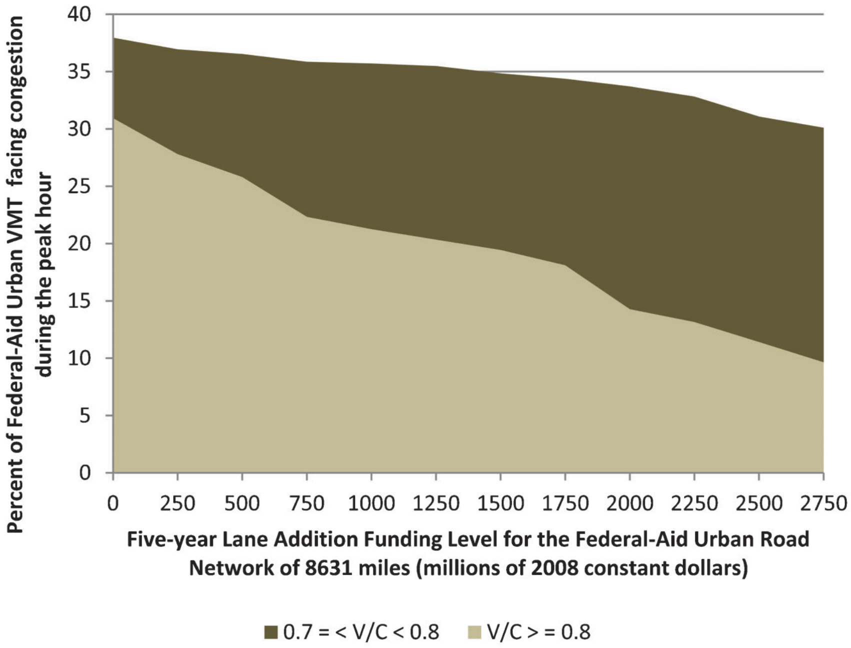


Figure 4.16 Percent of Federal-Aid Urban VMT facing congestion during the peak hour in 2029 under the Medium Deficiency Standard for triggering lane additions.

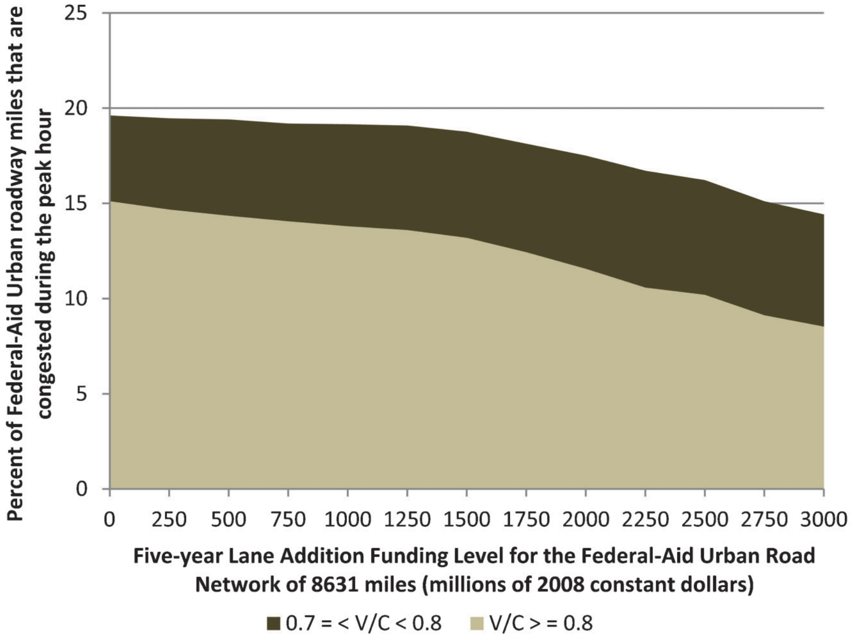


Figure 4.17 Percent of Federal-Aid Urban road miles congested during the peak hour in 2029 under the High Deficiency Standard for triggering lane additions.

TABLE 4.17
Peak hour Mobility Condition of Federal-Aid Urban roads in 2029 (by percent of uncongested and congested miles) with different funding levels under the High Deficiency Standard for triggering lane additions during the 2009–2029 period

Five-year Lane Addition Funding Level for the Federal-Aid Urban System (millions of 2008 constant dollars)	(1) Percent of Federal-Aid Urban roadway miles with peak hour $V/C < 0.7$	(2) Percent of Federal-Aid Urban roadway miles with peak hour $V/C \geq 0.8$	(3) Percent of Federal-Aid Urban Arterial miles with peak hour $V/C < 0.7$	(4) Percent of Federal-Aid Urban Arterial miles with peak hour $V/C \geq 0.8$	(5) Percent of Urban Major Collector miles with peak hour $V/C < 0.7$	(6) Percent of Urban Major Collector miles with peak hour$V/C \geq 0.8$	(7) Percent of State-Owned miles with peak hour $V/C < 0.7$	(8) Percent of State-Owned miles with peak hour $V/C \geq 0.8$	(9) Percent of Non-State-Owned miles with peak hour $V/C < 0.7$	(10) Percent of Non-State-Owned miles with peak hour $V/C \geq 0.8$
0	80.4	15.1	82.2	12.1	77.2	20.4	89	8.3	76.9	17.9
250	80.5	14.7	82.4	11.4	77.2	20.4	89.1	7.6	77.0	17.6
500	80.6	14.4	82.5	10.9	77.2	20.4	89.3	6.5	77.0	17.6
750	80.8	14.1	82.9	10.4	77.3	20.3	89.6	6.0	77.2	17.4
1000	80.8	13.8	82.9	10.1	77.3	20.3	89.7	5.1	77.2	17.4
1250	80.9	13.6	82.9	9.8	77.4	20.1	89.7	5.0	77.3	17.1
1500	81.2	13.2	83.3	9.4	77.8	19.7	90.3	4.5	77.5	16.8
1750	81.9	12.4	83.5	9.2	79.0	18.0	90.5	4.3	78.4	15.7
2000	82.5	11.6	83.9	8.6	80.1	16.7	90.8	4.0	79.1	14.7
2250	83.3	10.6	84.4	8.0	81.4	15.0	91.1	3.7	80.1	13.4
2500	83.8	10.2	85.1	7.4	81.4	15.0	91.9	3.4	80.5	13.0
2750	84.9	9.1	86.1	6.5	82.8	13.6	92.1	3.2	81.9	11.5
3000	85.6	8.5	86.8	5.9	83.5	13.0	92.8	2.6	82.7	10.9

TABLE 4.18
Peak hour Mobility Condition of Federal-Aid Urban roads in 2009 (by percent VMT facing uncongested and congested travel) with different funding levels under the High Deficiency Standard for triggering lane additions during the 2009–2029 period

Five-year Lane Addition Funding Level for the Federal-Aid Urban System (millions of 2008 constant dollars)	(1) Percent of Federal-Aid Urban VMT facing $V/C < 0.7$ during peak hour travel	(2) Percent of Federal-Aid Urban VMT facing $V/C \geq 0.8$ during peak hour travel	(3) Percent of Federal-Aid Urban Arterial VMT facing $V/C < 0.7$ during peak hour travel	(4) Percent of Federal-Aid Urban Arterial VMT facing $V/C \geq 0.8$ during peak hour travel	(5) Percent of Urban Major Collector VMT facing $V/C < 0.7$ during peak hour travel	(6) Percent of Urban Major Collector VMT facing $V/C \geq 0.8$ during peak hour travel	(7) Percent of State-Owned VMT facing $V/C < 0.7$ during peak hour travel	(8) Percent of State-Owned VMT facing $V/C \geq 0.8$ during peak hour travel	(9) Percent of Non-State-Owned VMT facing $V/C < 0.7$ during peak hour travel	(10) Percent of Non-State-Owned VMT facing $V/C \geq 0.8$ during peak hour travel
0	62.0	30.9	61.8	30.4	63.3	33.7	59.5	31.8	65.7	29.6
250	63.3	27.7	63.1	26.8	64.3	32.7	60.6	26.9	67.2	28.9
500	63.4	25.2	63.2	23.9	64.6	32.3	60.7	22.8	67.4	28.6
750	64.7	23.0	64.6	21.3	65.3	32.1	62.8	19.5	67.5	28.1
1000	64.8	20.7	64.7	18.6	65.4	32.1	63.0	15.8	67.5	27.9
1250	64.9	19.1	64.8	16.7	65.6	32.0	63.1	13.4	67.5	27.5
1500	66.4	17.1	66.6	14.4	65.7	31.9	65.5	10.4	67.7	26.9
1750	66.9	16.4	67.0	13.9	66.4	29.7	66.1	10.3	68.0	25.3
2000	68.0	13.6	68.0	10.9	68.0	28.0	67.1	7.0	69.3	23.3
2250	69.1	12.1	69.1	9.5	68.8	26.1	67.9	5.8	70.9	21.4
2500	70.9	11.3	71.3	8.5	68.9	26.0	70.9	4.8	70.9	20.7
2750	72.0	10.2	72.2	7.7	71.1	23.6	71.5	4.4	72.8	18.8
3000	73.6	8.8	73.9	6.2	71.8	23.0	73.5	2.7	73.8	17.7

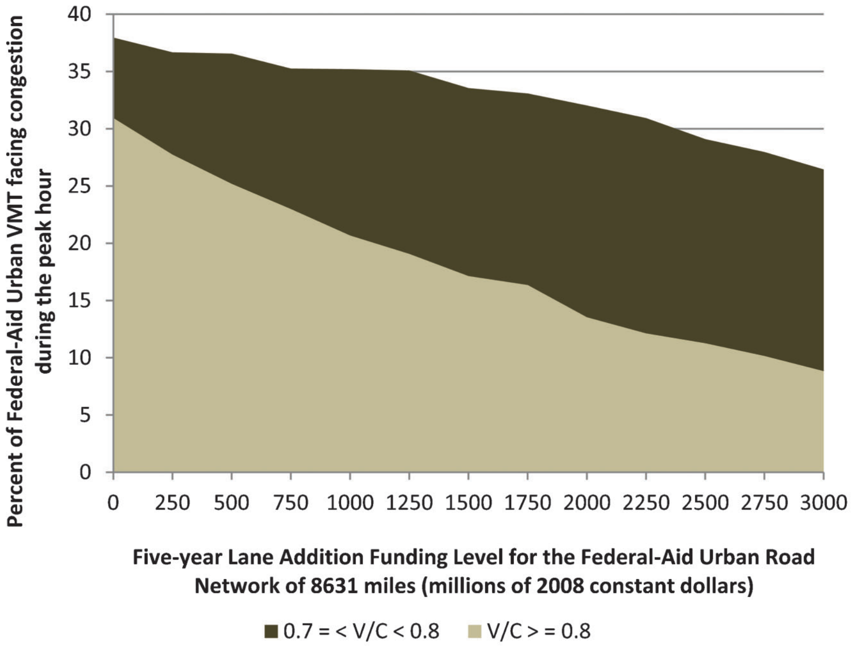


Figure 4.18 Percent of Federal-Aid Urban VMT facing congestion during the peak hour in 2029 under the High Deficiency Standard for triggering lane additions.

TABLE 4.19

Summary of the performance of the three deficiency standards for triggering lane addition in improving the peak-hour mobility condition of Federal-Aid Urban roads, by percent VMT, in 2029

		Value at No Funding for lane addition projects	Unit change in Value from No Funding to Break-point funding (per $100 million increase in five-year funding level)	Break-point funding level (millions of 2008 constant dollars per five years)	Value at Break-point funding level	Unit change in Value beyond the Break-point funding level (per $100 million increase in five-year funding level)	Value at funding level of $2500 million per five years	Value at funding level of $2750 million per five years	Value at funding level of $3000 million per five years
Low									
Percent of VMT traveling on roads experiencing a certain peak hour congestion level	V/C <0.7	62.0	0.14				65.6		
	V/C ≥0.8	30.9	−0.66	1750	19.3	−0.36	16.6		
Medium									
Percent of VMT traveling on roads experiencing a certain peak hour congestion level	V/C <0.7	62.0	0.23	2250	67.2	0.54	68.9	69.9	
	V/C ≥0.8	30.9	−1.15	750	22.3	−0.63	11.4	9.7	
High									
Percent of VMT traveling on roads experiencing a certain peak hour congestion level	V/C <0.7	62.0	0.23	1250	64.9	0.50	70.9	72.0	73.6
	V/C ≥0.8	30.9	−0.83	1750	16.4	−~0.61	11.3	10.2	8.8

5. SUMMARY AND CONCLUSION

The purpose of this research project was to analyze the impacts of changing the trigger standards of certain asset condition restorative projects and varying the available budget on the network-level asset condition for asset classes. The feasibility of creating a Budget-Constrained System Performance (BCSP) Curves to facilitate the network-level condition analysis for each of the four major asset classes was examined. For the performance categories of pavement condition, bridge condition, and mobility condition, system performance curves were built to show the level of performance that could be expected for any budget level and trigger standard.

The HPMS 2009 dataset and the HERS-ST software were selected to carry out the analysis for the pavement and mobility asset areas in this project. The software operation process was summarized in Chapter 2, and the modification of various settings was documented in appropriate locations in Chapters 2, 3, and 4.

5.1 Summary of the Results for Pavement Asset Class

For the pavement asset class, the impact of changing the pavement moderate and heavy rehabilitation project triggers and the budget available on the network-level pavement condition was examined for the State Urban road network, State Rural Arterials, and the Federal-Aid Urban road network. The performance measure used for the pavement asset class was percent of roadway miles meeting certain IRI condition threshold values. Three pavement rehabilitation trigger sets (deficiency standards) were developed and they were labeled as low, medium, and high. They are defined in Chapter 3, and they reflect different trigger values for labeling a road section as deficient in terms of pavement condition and placing such a section on a candidate list for pavement rehabilitation project implementation.

The following analysis results are contained in Chapter 3:

- The roughness condition of all three pavement road networks is highly influenced by the policy being used to trigger pavement rehabilitation. The higher the trigger standard, the higher the percentage of miles in good condition and the lower the percentage of miles in poor condition.
- For the State Urban road network of 2512 miles, as the funding level increases, the deficiency standard being applied to trigger pavement rehabilitation remains a significant factor in increasing the percent of road miles with smooth pavement ($IRI<120$) but progressively becomes a less relevant factor in decreasing the percent of road miles with rough pavement ($IRI\geq170$).
- For the State-Owned Rural Arterial road network of 4268 miles, switching from the low to the medium standard at any funding level results in a greater magnitude decrease in the percent of roads miles with pavement roughness of $IRI\geq170$ than switching from the medium to the High Deficiency Standard. Also, switching from the medium to the High Deficiency Standard at any funding level has an effect of greater magnitude in increasing the percent of smooth pavement miles than switching from the low to the Medium Deficiency Standard.
- For the Federal-Aid Urban road network of 8631 miles, switching from the low to the Medium Deficiency Standard at any funding level has an effect of greater magnitude in decreasing the percent of rough pavement miles than switching from the medium to the High Deficiency Standard. Also, switching from the medium to the High Deficiency Standard at any funding level has an effect of greater magnitude in increasing the percent of smooth pavement miles than switching from the low to the Medium Deficiency Standard.

5.2 Summary of the Results for the Mobility Asset Class

For the mobility asset class, the impact of changing the lane addition project triggers and the budget available on the network-level mobility condition was examined for the State Urban road network and the Federal-Aid Urban road network. This research study used the "Capacity Utilization" performance measures to construct budget-constrained performance curves for the mobility asset class. The two measures used to develop the curves were: (1) the percent of roadway miles experiencing congestion during the peak hour, and (2) the percent of VMT traveling through roads that experience congestion during the peak hour. Three lane addition trigger sets were developed and they were labeled as low, medium and high. They are defined in Chapter 4, and they reflect different trigger values for identifying a road section as deficient in terms of mobility condition and placing such a section on a candidate list for lane addition project implementation. The following results are contained in Chapter 4.

- For the State Urban road network of 2512 miles, the Medium Deficiency Standard has more cost-efficient performance than the Low Deficiency Standard at all funding levels in reducing the percent of road miles or VMT traveling on roads with peak hour congestion. Although, the High Deficiency Standard shows more cost-efficient performance than the Low Deficiency Standard at all funding amounts, the High Deficiency Standard does not seem to be more cost-efficient than the Medium Deficiency Standard at the highest funding levels.
- For the Federal-Aid Urban road network of 8631 miles, the effect of the deficiency standard on the network-level mobility condition is more obscure. The Medium Deficiency Standard demonstrates more cost-efficient performance than the Low Deficiency Standard in reducing the percent of VMT traveling on roads with peak hour congestion only at the highest funding levels. Similarly, the High Deficiency Standard demonstrates nearly the same cost efficiency as the Medium Deficiency Standard in reducing the percent of VMT traveling on roads with peak hour congestion at the highest funding levels.

5.3 The Safety Asset Class

For this research project, the horizontal and vertical alignment adequacy measures as reported in the HPMS 2009 data were examined to determine if they can be used to construct budget-constrained performance curves that can enhance decision-making in implementing safety restorative projects. As can be seen in Chapter 2, most urban road sections have no reported alignment adequacy information. Additionally, HPMS data does not contain crash rate information and there is no available information on intersection safety adequacy. This limits the usefulness of the alignment adequacy information. Furthermore, the process by which HERS-ST software estimates the influence of alignment correction (safety restorative action) on network-level roadway safety is flawed; the overall crash rate as well as fatality and severe injury rates are calculated for each functional class based purely upon the alignment adequacy measures and roadway geometry, without calibration to the currently observed metrics. It was therefore determined that development of budget-constrained system performance curves for safety management is currently infeasible, but could become feasible if the results of recent JTRP research efforts are utilized and extended in the future.

The safety screening tool developed for Indiana through SPR-3315 can identify high crash locations and screen the safety performance by geographical scope, roadway element, crash type criteria, and roadway feature. The backbone data contained in the tool consists of Indiana road links, intersections, ramps, bridges, and geometric inventory information. The tool could theoretically be linked up to a safety asset management software module for the purpose of evaluating network-level safety performance of the highway system in response to funding to implement countermeasures designed to address safety issues. This newly developed tool could also be used in conjunction with the findings of the currently ongoing SPR-3640 research study that is developing a geometry sufficiency index to evaluate the geometric adequacy of road cross-sections based on documented safety and speed effects. One of the purposes of developing this index is to evaluate current deficiencies throughout the network and to aid in prioritizing safety improvement projects.

5.4 Conclusion

This volume of the report presents the impact of modifying project-level treatment triggers and varying budget availability on the long-term network-level performance of the pavement and mobility asset classes. The analysis results were presented in the form of budget-constrained performance curves. This type of analysis can be conducted for any restorative treatment implemented on any transportation infrastructure asset class.

Conducting this analysis offers flexibility for asset managers to provide good levels of service on the physical transportation infrastructure by strategically responding to anticipated changes in the consistent annual budget level over a multi-year period.

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About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at:
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