ABSTRACT

The maintenance of pavements, structures and bridges, and other transportation assets has become a challenge for the Virginia Department of Transportation (VDOT). These challenges include effective allocation of financial resources, communication improvement between upper and lower level maintenance entities in the department, ability to perform cross-asset selection, and incorporation of risk analysis in the decision making process. The Center for Risk Management of Engineering Systems and the project team have developed a risk assessment and management framework to address these problems. This new methodology, which uses condition (lifetime remaining) and cost as indexes of performance, would allow VDOT to target short-term and long-term goals, and to coordinate for maintenance activities. Indeed, the framework developed will help the department maintain their transportation assets in a more efficient manner and prevent unforeseen failures.

1 INTRODUCTION

The Virginia Department of Transportation, VDOT, is responsible for maintaining the country’s third largest highway system (VDOT: Info & Services, 2002). The system includes highway, primary road, and bridge assets. VDOT has inadequate maintenance management systems (JLARC, 2002). The overall goal of this project was to help VDOT manage the maintenance of Virginia’s roads and highways effectively by developing a systemic risk-cost-benefit modeling and analysis framework. Additionally, the methodology was tested on VDOT data for the residency, district, and the Asset Management Division levels.

Figure 1 shows the organizational structure of VDOT. The state level of the organization is the Asset Management Division, which supervises the nine districts. Each district is then divided into several residencies, for a total of 45 residencies in all of Virginia. Then, each residency is separated into area headquarters. There are 244 area headquarters in the state. The maintenance decisions are made mostly at the residency level with some bridges maintained at the district level.

Figure 1. VDOT organizational structure.
outside factors changing the condition of the asset in the future.

The methodology developed by this project incorporates proven techniques in the areas of risk management, resource allocation, cost-benefit modeling, and trade-off analysis. This methodology is a series of processes that take the decision-maker from the initial data collection to the Asset Management level. This methodology provides a general and repeatable risk-based framework for asset management that was developed based on an understanding of VDOT's needs and current processes.

This project was conducted through the University of Virginia Center for Risk Management in collaboration with the Virginia Transportation Research Council, VTRC. It was supervised by Professor Haimes and Professor Lambert of the Systems and Information Engineering Department.

2 METHODOLOGY OVERVIEW

The team adopted a five-step process to address the situation facing VDOT. This methodology focused the decision power at the asset level. Therefore the risks, costs and benefits were all calculated for each individual asset and then combined for the total costs and benefits at the Regional, District and Asset Management level. Figure 2 demonstrates the step-by-step process.

The first step in this process is to gather all of the needed information for the asset in question. This was done through the use of current databases and management officials in VDOT. Typically, the information that was gathered would specify the asset’s current condition and its risk of further deterioration or importance to the transportation infrastructure. This information would be carried through the operational and contingencies filters to prioritize the assets as to those that need urgent attention and those that can wait.

Any assets that were determined to need maintenance would be sent through the Multiobjective Decision Tree, or MODT (Haimes, 1998). The tree uses the available maintenance actions as the different possible decisions and the probability of severe weather for the chance node. This is done for two decision periods so that short-term and long-term costs can be estimated as well as the lifetime remaining for an asset at the end of the second period. A decision is then made from the output of the tree and sent to the Residency level for further analysis.

The Residency level will gather all of the decisions made for each of the assets in its jurisdiction to make a larger plan. A tradeoff analysis is conducted at this level to decide what the best maintenance actions are that help the larger area. These decisions are then carried to the next higher level, the District level. Again the best decision is made and the costs are sent to the Asset Management level to specify the monetary needs throughout the state, thus making it an Asset Management methodology.

3 ASSET CLASSIFICATION

Asset classification required a large amount of information on assets. The team accomplished the feat of gathering this information by taking advantage of current VDOT facilities and employees. VDOT currently maintains a number of databases containing much of the information which can be utilized for asset classification. The Pontis, Pavement Management Program (PMP), Inventory and Condition Assessment System (ICAS), Integrated Maintenance Management Program (IMMP), and Integrated Maintenance Management Systems (IMMS) were used to obtain asset information such as asset ID, asset group, annual average daily traffic (AADT), % truck AADT, location (county, residency, district), condition index, and network membership. Further information was gathered through interviews with VDOT engineers, i.e. Tanveer Chowdhury, Jose Gomez.

Once the team acquired this information, an asset classification plan was developed. For the purpose of maintenance, an asset may be classified as a must, non-must, or reconstruction. The asset classification flow is shown in Figure 3.
An asset may be allowed to deteriorate in condition as it may be scheduled for rehabilitation or replacement. Such asset is classified as a reconstruction. If an asset is not a reconstruction candidate, then the priority or urgency level for maintenance associated with the asset was identified. The explicit identification of high-priority maintenance assets (must) vs. lower-priority assets (non-must) is based upon the systemic consideration of maintenance risks. Must assets are in critical condition or are critical to the operation of the transportation system. As- assets that undergo preventive maintenance actions are also considered musts because such actions prevent further deterioration. The remaining assets are categorized as non-musts.

There are two filters for the remaining assets. The operational filter uses the characteristics of an asset such as its condition, annual average daily traffic, and its road network which help determine the priority level of the asset. This filter is based mainly on day-to-day operations and real-time measurement of asset characteristics. A set of criteria was developed to differentiate between a must asset and a non-must. Once an asset is classified as a must, it becomes a high-priority asset. The non-must asset undergoes another filter—the contingency filter. This filter is driven by abnormal or extreme events that may occur if maintenance activities are not performed on the assets. If an asset is determined to be at high-risk, then it becomes a must asset and is given high priority.

### 3.1 Operational Filters

To determine if an asset falls under the reconstruction category, its condition is considered. If an asset is in very poor condition, then it considered for replacement or rehabilitation. For pavements, very poor condition refers to a critical condition index (CCI) ≤ 30. For bridges, very poor condition refers to a general condition rating (GCR) ≤ 2.

The asset that does not fall under the reconstruction category is then classified into must or non-must. An asset is considered a must if, for pavements, CCI ≤ 60, or, for structures and bridges, GCR ≤ 4 and, any of the following is true:

- It is part of the Strategic Highway Network, Hazardous Material Network, or National Highway System.
- Its annual average daily traffic (AADT) exceeds 25,000.
- Its percent truck AADT exceeds 10.

These rules were chosen based on previous research. The events specified in these rules have been known to cause serious deterioration in assets. An asset that is not classified as a reconstruction or a must is then considered a non-must according to the operational filter.

### 3.2 Contingency Filters

The non-must asset from the operational filter can still become a must if it passes successfully through the contingency filter. The contingency filter focuses on the outside effects on the asset rather than the internal characteristics and continues to prioritize assets. This filter allows the asset to be tested against potential events and is driven by abnormal or extreme events that may occur if maintenance activities are not performed on the assets. The events are characterized by their sources (grouped according to likelihood) and consequences. The risk source categories are arranged in increasing probability of occurrence with more priority given to the prevention or minimization of risk sources than occur more frequently. The consequences brought about by non-maintenance and other risk scenarios are also enumerated and grouped into categories arranged in decreasing level of severity.

The risk severity matrix shown in Figure 4 is used to identify the main source of risk to the transportation asset and the most likely effect brought about by the asset failure. The associated risk level signifies the importance of maintaining the asset. Assets that are exposed to frequently occurring sources of risk and whose non-maintenance can lead to severe effects are given higher priority in maintenance. High-risk assets are classified as must assets. Otherwise assets are classified as non-musts.

![Risk severity matrix](image)

Figure 4. Risk severity matrix.

To use the risk severity matrix, one identifies the risk source category that the asset is prevalently exposed to, and the risk effect that can be brought about by non-maintenance. Once the pair of risk source and risk effect is obtained, the risk severity matrix is used to identify the asset risk level as high risk, medium risk, or low risk.

### 4 MULTIOBJECTIVE DECISION TREE

The cost-benefit analysis was conducted using a multiobjective decision tree (MODT). The MODT for this methodology is a graphical representation of the possible maintenance decisions and the risk of severe weather conditions for an asset over two periods (Figure 5). The pe-
period length is a given length of time between maintenance actions determined by the user. The MODT produces expected values for the short-term cost (the cost in period 1), the long-term cost (the cost in period 2) and the lifetime remaining (the lifetime remaining at the end of period 2). The remaining life is the anticipated number of years that an asset is in acceptable condition under normal conditions given that no further maintenance is performed. Based on these three critical variables, the MODT has three objectives:

1. Minimize short-term cost
2. Minimize long-term cost
3. Maximize lifetime remaining

Figure 5. Multiobjective Decision Tree (MODT).

Solving the MODT gives the expected costs and lifetime remaining for each set of possible maintenance actions for one asset. One combination of possible maintenance actions over two periods is called a policy and one asset has many policies. Some policies can be removed from the analysis because they are inferior with respect to the established objectives. The remaining solutions that satisfy one or more objectives are the Pareto optimal solutions.

The MODT can produce hundreds of policies for a given asset. To aid the decision-maker in choosing a policy, the results must be effectively displayed in graphs. Graphing the set of Pareto optimal policies with respect to the short-term cost, long-term cost, total cost and lifetime remaining shows the decision-maker any general trends (Figure 6). The decision-maker can visually assess the consequences of the trade-offs of the three objectives. Further, the user can zoom in on a range of particular interest to view those policies in different graphs or a table. Now that the solution set is narrowed to a manageable size, the decision-maker can use the visual displays and apply engineering and management expertise to choose up to three policies for each asset.

![Figure 6. An example of the Pareto optimal solutions for an asset.](image)

5 AGGREGATION

The analysis done at the asset level must be carried up into a state wide plan in order for this methodology to become an Asset Management policy. This is most effective when information is collected in residency and district increments rather than jumping to one compilation of all assets at the Asset Management Division Level. Therefore, the first step is to aggregate the asset level maintenance policies to the appropriate Residency and then to the District level.

5.1 Residency Level Strategies

There are 45 Residencies in Virginia. The managers of each residency will be given the information for the must assets. Since at the asset-level, the user is allowed up to three policies per asset, it is likely that several policies will be assigned to each asset. As a result, the Residency level must decide the best strategy for the larger area. Each Residency level strategy includes every asset within the jurisdiction, and every possible combination of asset policies are made into strategies. Therefore, the number of strategies is dependent on the number of asset policies for each bridge or pavement.

The total costs, both short-term and long-term, are calculated for each Residency level strategy by summing the costs of the asset policies. The lifetime remaining of the assets within a Residency is represented in ranges of years. All strategies are then graphically displayed as scatter plots.
with the short-term on the y-axis and the long-term cost on the x-axis (Figure 7). Finally, any bounds due to budget or expectations for lifetime remaining are graphically represented in the analysis with lines. The decision maker then refers to the calculations provided to choose what strategies best satisfy the needs of the area. Again, they are allowed up to 3 strategies to carry to the District level.

5.2 District Level Strategies

Each Residency level decision is aggregated to one of 9 Districts within Virginia. The same procedure performed at the Residency level is conducted at the District level. This process is an examination of all possible combinations of District strategies, taking into account budgetary and performance constraints. The short-term and long-term costs are calculated as well as the total cost. All lifetime remaining are also collected into ranges of years that represent the assets within the District. These strategies are displayed on a scatter plot comparing short-term and long-term costs (Figure 8). A tradeoff analysis then is conducted at the District level by VDOT officials that minimizes cost while maximizing the lifetime remaining. The major difference between this level of management and the Residency level is that a single District level strategy is chosen. This is then given to the Asset Management Division, which allocates funds to each District according to their current needs.

Figure 7. Sample Residency level strategy graph.

Figure 8. Sample District level strategy graph.

6 RECOMMENDATIONS

The following recommendations have been developed for VDOT:

- Design and implement a software decision tool for this framework. This tool will increase the acceptability to personnel and contribute by lowering the impact on training and employee numbers.
- Implement appropriate databases that will provide our methodology with the necessary data to perform the analysis. These databases will ensure the accuracy and integrity of all transportation asset data.
- Develop accurate deterioration curves or models for specific transportation assets, which will represent the relationship between asset condition and remaining life.
- Identify the problems that would arise due to the lack of good knowledge management practices in the institution.
- Provide employees with literature material and efficient training sessions. The hiring of experts in the fields of risk assessment and management is fundamental during the introduction of this new methodology.

These recommendations will enhance the functionality of the methodology. The conditions of individual transportation assets and asset systems (cross-asset selection) will be enhanced without increasing the expenditure. The methodology will prevent VDOT from creating unnecessary surpluses and deficits. Additionally, unlike current maintenance practices, the framework includes uncertainty in the decision making process, which will benefit the department in case unexpected incidents occur.
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