FINAL CONTRACT REPORT

RISK-BASED ASSET MANAGEMENT METHODOLOGY FOR HIGHWAY INFRASTRUCTURE SYSTEMS

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ABSTRACT

Maintaining the infrastructure of roads, highways, and bridges is paramount to ensuring that these assets will remain safe and reliable in the future. If maintenance costs remain the same or continue to escalate, and additional funding is not made available, the highway agency may need to reduce new construction or cut back on maintenance, or both. There is a close relationship between the cost of optimally scheduled preventive maintenance versus the cost of emergency maintenance or replacement. The study develops a systemic risk-based asset management methodology to manage the maintenance of highway infrastructure systems. The decisionmaking methodology is used to harmonize and coordinate the actions of the different units and levels in a hierarchical organization. The systemic methodology enables the filtering and assessment of assets for maintenance while addressing the potential for extreme events. The methodology balances the costs, benefits, and risks of maintenance and inspection policies as applied to various types of assets. Three objective functions are used in evaluating options and strategies: minimizing short-term cost, minimizing long-term cost, and maximizing the remaining service life of highway assets. A constraint function harmonizes the remaining service life across assets to eliminate infeasible options. The methodology is generally applicable to the asset management of large-scale dynamic systems that exhibit characteristics similar to those of highway systems.

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INTRODUCTION

Over the past fifty years, the United States has been engaged in constructing the National Highway System (NHS). The NHS is a 256,000 km system that includes the interstate highway system, strategic military highways, and major arterial roads. While the NHS accounts for only 4% of the roadways in the United States, it carries 40% of all highway traffic and approximately 75% of all heavy truck traffic. As the system ages, roads and bridges are deteriorating faster than they can be repaired or replaced. According to The Road Information Program (TRIP) [2003], 32% of the nation's major roads are in poor or mediocre condition, while 27% of the bridges are structurally deficient or functionally obsolete. The American Association of State Highway and Transportation Officials (AASHTO) reported that in FY 2000, $64.5 billion was spent by all levels of government for highway and bridge capital improvements [AASHTO 2002]. In order to maintain the physical condition and performance characteristics of the highway system over twenty years, this level of investment needs to increase to $92.0 billion annually [AASHTO 2002]. In the same report, AASHTO also stated that an annual investment of $125.6 billion is needed to improve the overall conditions of the nation's roads and bridges. With the assistance of the US federal government, the fifty states have begun to shift their focus from construction to repair and maintenance of the existing infrastructure. The emphasis is on intelligent decisionmaking so that maintenance projects are prioritized to yield the most benefit for the lifecycle cost of each highway asset.

BACKGROUND

The literature associated with infrastructure maintenance focuses on low-level details such as materials research and structural degradation research. The strategic management aspect is largely ignored. Recognition of the maintenance management shortfall has resulted in some research initiatives in this area over the past 10 to 15 years. The Federal Highway Administration (FHWA) defines asset management as "a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized logical approach to decisionmaking. Thus, asset management provides a philosophy of approach for handling both short- and long-range planning" [FHWA 1996]. There is a growing movement to develop methodologies supportive of asset management [FHWA 1999a, 1999b]. While there is general agreement that such methodologies should be developed, there is little consensus as to how it should be done.

Due to the critical nature of bridge failures, initial work in this area focused on modeling the maintenance requirements for bridges. The most prominent tool for managing bridge maintenance is Pontis, developed by Cambridge Systematics [Thompson et al. 1998]. The tool uses a Markov chain to model the deterioration of bridge components and the impacts of maintenance actions on those components. Maintenance actions are selected and prioritized based on incremental cost-benefit analysis; the action producing the most benefit at the least cost is selected first. Several pavement management systems have been developed. The most widely used pavement management software is MicroPaver produced by the US Army Corps of Engineers Research Laboratories [Shahin 1994].

Several researchers have attempted to build mathematical models to optimize maintenance actions that encompass an entire statewide system. Sadek et al. [2003] have developed an integrated infrastructure management system that maximizes the overall condition of the transportation system subject to budget constraints. The budget allocation module has two levels: transportation system and individual component. Wang and Liu [1997] present a network optimization system for pavements which maximizes pavement network performances given a known budget in future years. Fuzzy sets are used to model coefficients of the pavement condition factors. Worm and van Harten [1996] have constructed a model that minimizes the net present value of future maintenance costs while accounting for the economies of scale in road maintenance. Another approach is to model the highway network with respect to traffic loads to determine the optimal maintenance priorities [Donaghy and Schintler 1998]. These are single-objective models which are limited in their real-world utility and practicality; unfortunately, they seem to be the trend in highway infrastructure maintenance management.

A limitation of a single-objective approach is that a state highway agency has many legitimate and important conflicting and non-commensurate objectives. These include minimizing cost and risk of failures while maximizing the condition of the highways, access to all areas of the state, public satisfaction, public safety, traffic flow, and economic benefit. Any attempt by strategymakers to attach monetary value to these objectives would be largely speculative, since there is little or no supportive data. The underlying problem with these single-objective cost-benefit models is that they attempt to assign weights to concepts, such as lives lost, economic benefit to the state, and accessibility, in order to translate them into monetary units. As a result, the solutions to these types of models tend to be unstable and lack credibility. Small changes in the values of input parameters often lead to significant changes in the optimal maintenance program [AASHTO 2001].

The multiobjective nature of the situation in a decisionmaking framework has been addressed in several works. Fwa et al. [2000] have developed a genetic algorithm-based approach to determine the Pareto optimal frontier for pavement maintenance options. Chan et al. [2003] employ a two-stage genetic algorithm procedure for a central authority to allocate resources to regional or district agencies. In the first stage, only the needs and requirements of regional or district agencies are considered. In the second stage, the constraints and requirements of the central authority are imposed to arrive at a solution. For investment decisions, Hsieh and Liu [1997] presented a 0-1, nonlinear, multiobjective knapsack problem that is solved using heuristics. A multiobjective resource allocation methodology for highway safety projects was presented by Chowdhury et al. [2000]. The minimization of cost and the maximization of safety based on crash severity levels were the main objectives used. A goal programming methodology was developed by Ravirala and Grivas [1995] for integrating pavement and bridge programs. Gharaibeh et al. [1999] presented a geographic information system-based methodology for managing highway assets. Multiple performance measures were used in project selection.

Some researchers have focused on accurate cost estimation and financing as opposed to the overall optimization model. Sobanjo [2000] uses fuzzy probabilities to assess bridge costs and employs a utility-based economic analysis technique to select among maintenance alternatives. Meanwhile, Dornan [2000] discusses the long-term implications of maintenance deferral for roads and bridges and suggests methods for financing the operation and maintenance of these assets in order to have the resources available to properly maintain them. He further suggests that avoiding the costs associated with deferred maintenance will lead to significant savings in the long run.

Some researchers have applied risk analysis to maintenance decisionmaking. According to Paté-Cornell [2002b], the important inputs to the optimal allocation of resources are the magnitude of the risk and its uncertainty. Probabilistic risk analysis is used by Paté-Cornell [2002a, 2002b] to assess risk and its uncertainty, and prioritize the mitigating options. Bayesian probability is used to perform analysis with the evidence obtained from past experiences of failure, surrogate data, test data, engineering models, and expert opinion [Paté-Cornell 2002a]. Matthews et al. [2002] acknowledge that risk analysis contributes significantly to life-cycle assessment, and improves the life-cycle results and implications. Chang and Shinozuka [1996] have presented a life -cycle cost analysis which considers the risk of natural hazards, particularly earthquakes. Amekudzi and McNeil [2000] state that data and model uncertainties are present in highway performance estimates. They have developed an approach that captures data- and model-induced changes in the expected value and variability of estimates. Easa et al. [1996] offers a reliability-based model which predicts thermal cracking of pavements and relates it to cold winters, spring thaws, and daily cyclic thermal loading.

Risk analysis is important to highway maintenance because extreme events can occur and lead to failure of the highway system. (Extreme events are defined as those that cause catastrophic failure but have a low likelihood of occurrence [Bier et al. 1999]). The connection of risk analysis to maintenance has not been fully studied. In addition, there is a dearth of systemic, multiobjective, and risk-based maintenance methodologies that can solve the problems facing a highway agency's maintenance program. This situation leads to a definite line of study: how can the highway agency efficiently allocate its limited resources statewide to achieve the best possible system performance as measured by multiple, non-commensurate, conflicting objectives? How can the agency accomplish this while considering the short- and long-term costs as well as reliability and public safety? More specifically, given a set of possible maintenance actions, how can engineers and other agency officials select best and acceptable proposals that will maximize the benefits to the state while minimizing the associated costs and risks?

Decisionmakers need an asset-management methodology for selecting efficient strategies to maintain roads and highways. This methodology should be grounded in risk-cost-benefit modeling principles, utilize resources such as existing highway agency databases, and provide a set of tools and repeatable methods that can be used in decisionmaking. The innovation of this paper is the development of a methodology that incorporates and investigates the risks involved in the asset management of highway infrastructure systems. This paper presents a specialization of the risk severity matrix described in the Risk Filtering, Ranking and Management (RFRM) methodology by Haimes et al. [2002]. The scope of the paper is 1) identifying the sources and effects of risk to highway maintenance, 2) developing a classification scheme for highway assets, 3) presenting a tradeoff analysis for highway options, 4) aggregating lower-level options for hierarchical systems, and 5) presenting application examples demonstrating the asset management methodology.

DEVELOPMENT OF METHODOLOGY

The methodology developed for the maintenance of the agency's highway infrastructure builds on theory, methodology, and practice in risk assessment and management. It was developed and tailored to evaluate the costs, benefits, and risks of maintenance and to standardize asset inspection policies. Three objective functions are used: minimize short-term cost, minimize long-term cost, and maximize the remaining life of the roads and highways.

The methodology can be used to harmonize the remaining life of assets. Assets which are found in the same location are coordinated to require maintenance at the same periods in order to minimize work backtracking and expenditure. For example, pipes which are located under the roads are scheduled to be replaced at the same time as the pavement overlay. The highway agency benefits by having evenly distributed maintenance expenditures through assets being maintained at different periods. With this system of evenly distributed maintenance and expense, the highway agency need not pass over some assets due to funding constraints. The developed risk-based methodology is shown in Figure 1 and discussed below.

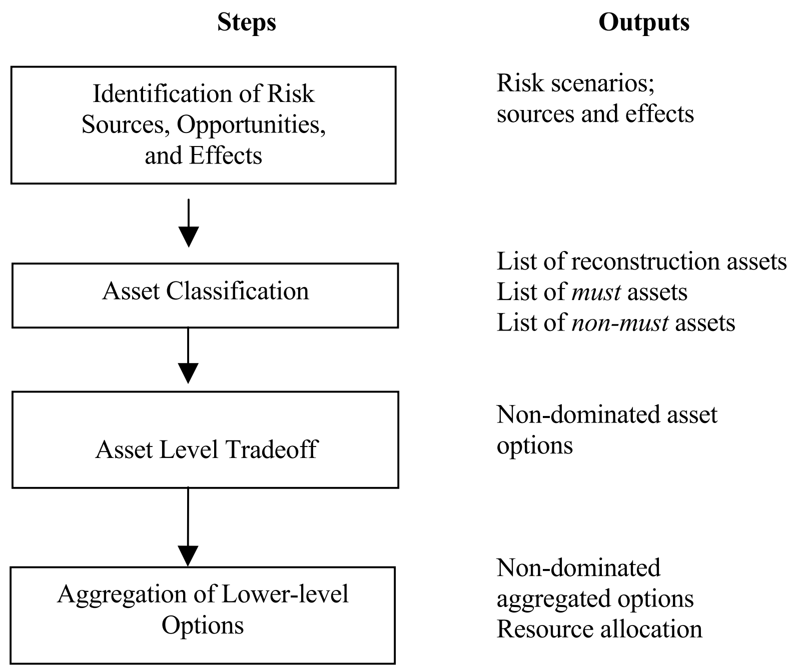


Figure 1. Steps in applying the risk-based asset management methodology for highway infrastructure systems

A. Identification and Classification of Sources, Opportunities, and Effects of Risks

The highway infrastructure is subject to numerous sources and causes of failure. Maintaining the system is a complex, large-scale activity that both affects and is driven by many elements. Local, regional, county, and state constituencies, political entities, power brokers, and stakeholders—all have legitimate interests in this critical system. A better understanding is needed of the maintenance issues facing the highway agency, and the processes within which current maintenance activities are identified, designed, scheduled, financed, performed (internally or by contract), and inspected for quality assurance.

Hierarchical Holographic Modeling (HHM), a holistic and comprehensive analytical methodology [Haimes 1981, 1998; Lambert et al. 2001], is employed to identify the sources, opportunities, and effects of risks that affect the performance and reliability of roads and highways. The objective is to identify all possible sources of risks and ensure that "no stone is unturned" in understanding the maintenance activities of the agency. A hierarchical holographic model for the surface highway system is developed through interviews and meetings with highway agencies regarding maintenance efforts. In addition, literature on maintenance and highway issues is used to identify sources and effects of risks to highway infrastructure. Figure 2 presents a sample HHM of the maintenance process.

B. Asset Classification Incorporating Potential for Extreme Events

The highway assets that compete for maintenance funding are varied and numerous. With limited available funding, it is necessary to develop an effective classification scheme that enables decisionmakers to determine the priority and urgency level of each asset. The classification process filters the number of assets in need of maintenance down to a more manageable level so that the most critical can receive appropriate attention and tradeoff analysis can be performed. The vulnerability of the highway agency's maintenance activities to extreme events is studied by identifying risk scenarios that affect an asset's ability to meet performance or service-level criteria. The potential impacts of extreme events on the asset help guide the asset classification process.

For the purpose of maintenance, a highway asset may be classified as *must, non-must,* or *reconstruction.* Figure 3 shows the asset classification flow. An asset's condition may be allowed to deteriorate if it is scheduled for rehabilitation or replacement. Such an asset is classified as a *reconstruction* in the agency's construction or improvement plan, and it is removed from further consideration in the maintenance division. If an asset is not a *reconstruction,* then its maintenance priority or urgency level is 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 highway system. Assets that undergo preventive maintenance actions are also considered *musts* because such actions prevent further deterioration.

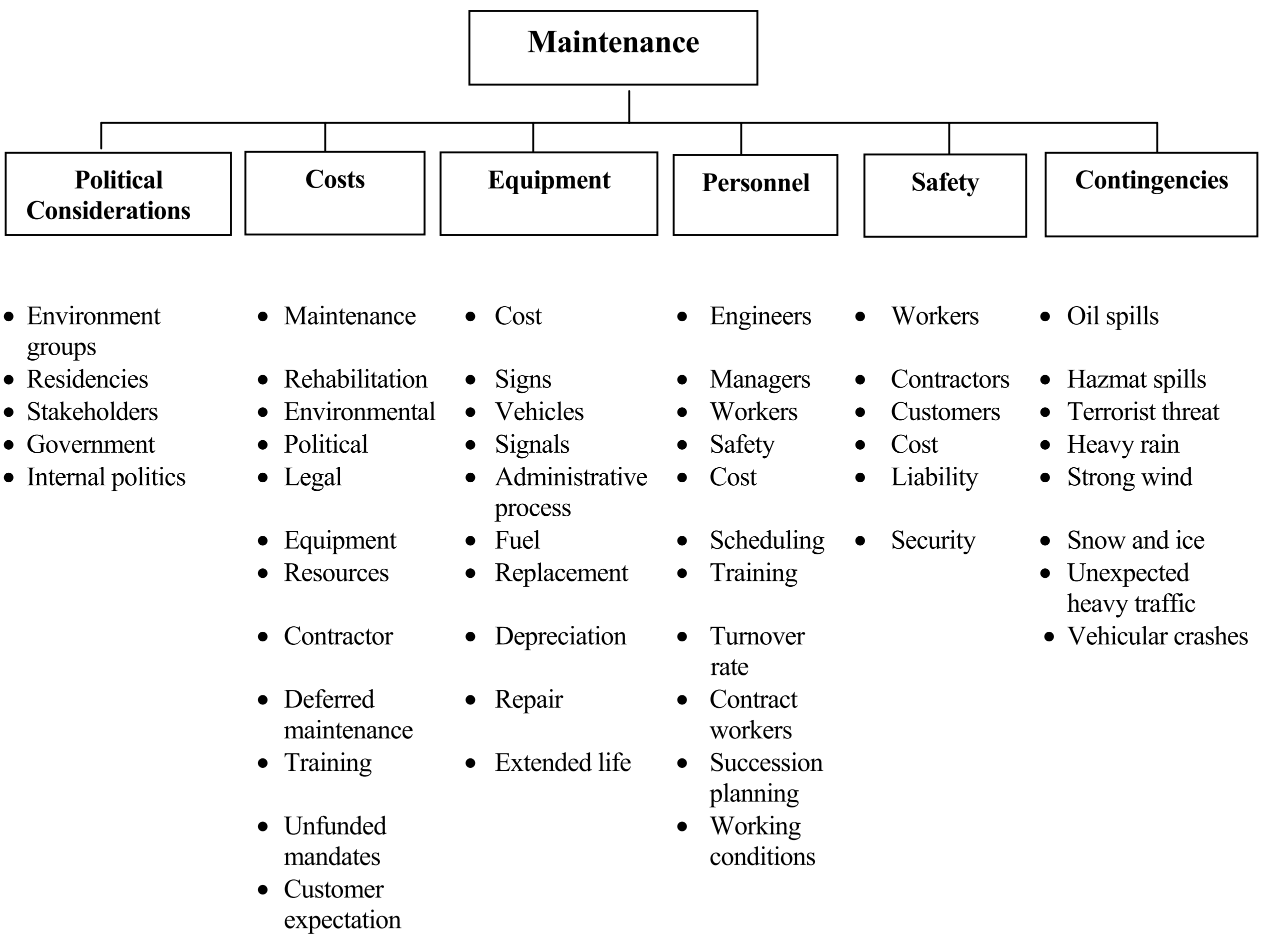


Figure 2. Hierarchical holographic model showing a sample of the sources of risks to highway infrastructures

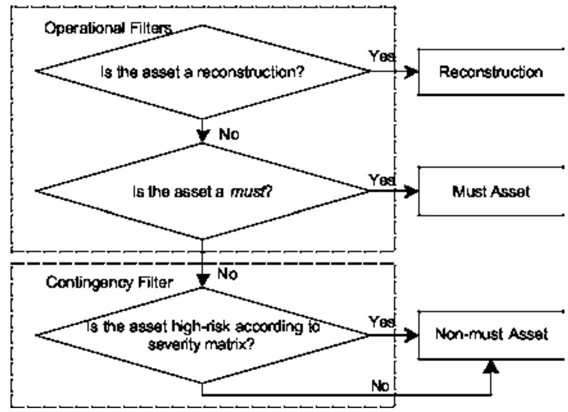


Figure 3. Process for identifying assets that belong to *reconstruction, musts,* and *non-must*s classes

Two types of filters are developed for the remaining assets. A set of criteria is developed to differentiate between a *must* asset and a *non-must.* The filter criteria can be controlled by the decisionmakers to make it more or less sensitive. The first type of filter is based mainly on day-to-day operations and real-time measurement of asset characteristics such as condition, annual average daily traffic, safety concerns, and its road network classification. Once an asset is classified as a *must,* it becomes a high-priority asset. Table 1 presents examples of operational filters that are used for classifying assets. The filters are developed through interviews with highway agency personnel and a review of available transportation literature. The suggested cut-offs can be modified by the user and additional filters can be utilized. The *non-must* asset goes through the second type of filter—the contingency filter. This is driven by abnormal or extreme events that may occur if maintenance activities are not performed. The contingency filter uses the risk severity matrix found in Figure 4. This is a specialization of the risk matrix for scenario filtering and ranking used in the Risk Filtering, Ranking, and Management (RFRM) method developed by Haimes et al. [2002].

Table 1. Examples of criteria used to differentiate pavement and bridge *reconstruction* and *must* assets to determine asset management priority

Classification	Characteristic	Pavement Condition	Bridge Condition
Reconstruction	-	Critical condition index (CCI) = 30	General condition rating (GCR) = 2
Must	Part of Strategic Highway Network, Hazardous Material Network, or National Highway System	CCI = 60	GCR = 4
Must	Annual average daily traffic (AADT) = 25000	CCI = 60	GCR = 4
Must	Truck traffic = 10% of AADT	CCI = 60	GCR = 4

Figure 4 shows the risk severity matrix used to identify the main sources of risk to the highway asset and the most likely types of effects brought about by the asset failure. The associated risk level signifies the importance of maintaining the asset. Assets exposed to frequently-occurring sources of risk and whose non-maintenance can lead to severe effects are given higher maintenance priority and are classified as *musts*. The risk severity matrix is used to identify the asset's prevalent source of risk and the effect that can be brought about by non-maintenance.

Then the matrix is used to identify the asset's risk level as high, medium, or low. Table 2 presents a list of sources of risk. Priority is given to preventing or minimizing those that occur more frequently. Examples of the consequences brought about by non-maintenance and other risk scenarios are found in Table 3.

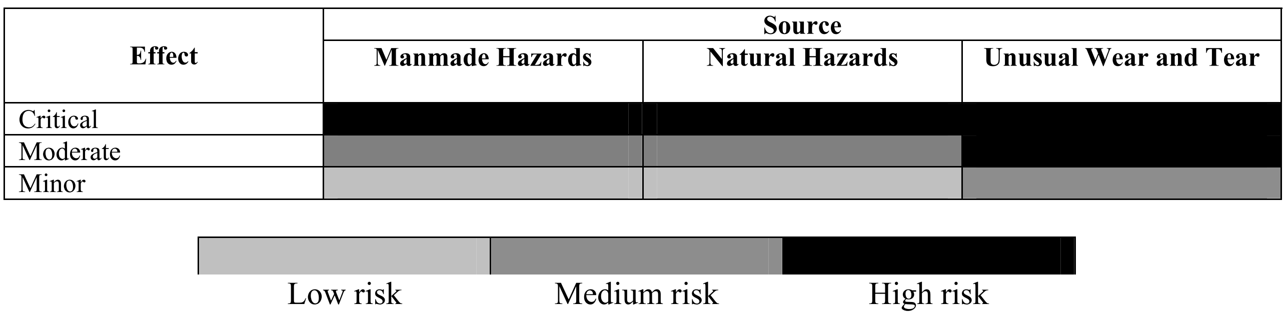


Figure 4. Risk severity matrix used for *non-must* assets to determine final asset classification. An asset becomes a *must* if it has a high-risk exposure level

Table 2. Categories of risk sources and examples for identifying most prevalent source of risk to the asset

Risk Source	**Examples**
Man-made hazards	Oil spill Hazardous material spill Terrorist threat
Natural hazards	Heavy rain Strong wind Heavy snow and ice
Unusual wear and tear	Unexpected heavy traffic Vehicular crashes

Table 3. Categories of risk effects and examples for identifying most likely consequences brought about by asset non-maintenance

Risk Effect	Examples
Critical	Multiple fatalities Multiple injuries Complete loss of service Loss of military mobility Total area inaccessibility Major traffic disruption
Moderate	Partial loss of services Partial lane closure Moderate number of fatalities Moderate number of injuries
Minor	Slight increase in maintenance costs Temporary traffic disruption

C. Tradeoff Analysis at the Level of Individual Assets

For each asset, there can be several maintenance options. For instance, given a road in good condition, the decisionmakers still can choose the type of sealer to apply—chip seal, crack seal, or slurry seal. To gain understanding of the benefits and risks of maintenance options for an asset, a multiobjective decision tree (MODT) [Haimes et al. 1990; Frohwein and Lambert 2000; Frohwein et al. 2000] is employed. MODT enables consideration of different maintenance options and their impacts on future action. Accelerated deterioration is caused by several factors, including poor and inadequate design, wear, moisture intrusion, and environmental effects [Hastak and Baim 2001]. Chlorides used for de-icing and heavy traffic are risk factors that cause increased deterioration. When MODT is applied, uncertainty brought about by changing weather conditions is expressed in terms of the asset's remaining life and is explicitly considered in the decisionmaking process. In this paper, two types of weather are considered: normal and severe weather. Because weather conditions affect the asset, the expected values of the objective functions are obtained by averaging-out the values across the different weather types that occur.

The structure of the MODT is shown in Figure 5. The multiobjective decision tree is also used to estimate the expected cost of each maintenance action and predict the remaining life of the asset. The maintenance options are evaluated in terms of the costs of implementation now (short-term) and in the future (expected long-term), taking into account the expected remaining life of the assets. 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. The *initial remaining life* is the asset's condition at the start of its analysis; this assessment is provided by the analyst or decisionmaker. In MODT analysis, as actions are performed, extreme conditions are experienced, or a period passes, the estimate of the remaining life is adjusted accordingly.

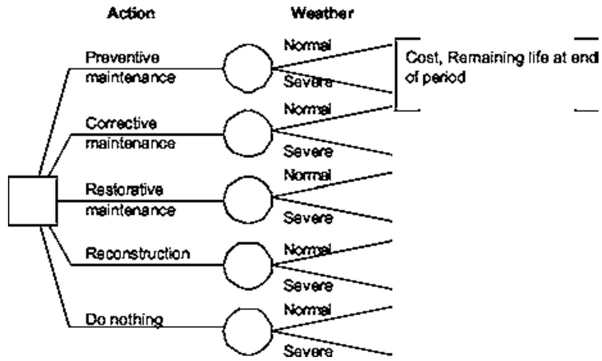


Figure 5. Structure of a single-period multiobjective decision tree for asset management of highway infrastructures. Multiobjective decision trees are used for multiple periods.

The MODT is not applied to individual assets. For some, the choice of maintenance action is straightforward. For assets where decisions would impact future action, MODT can be used to consider different scenarios and their impacts. When several assets are in the same condition and experience the same environmental and traffic conditions, only one decision tree is constructed, with the same results applicable to the similar assets. The highway agency has the flexibility to decide what time period to use between decisions. The application of MODT can produce multiple choices for a given asset. It is important to help decisionmakers understand and visualize the tradeoffs that are involved so that more informed choices can be made.

D. Aggregation of Maintenance Options

The highway infrastructure is an example of a large-scale system. Li and Haimes [1991] describe that a large-scale system has a hierarchical decisionmaking structure consisting of one or more levels. In each level, there may be several organizational units, each with its own decisionmaking objectives and constraints [Anandalingan 1988; Shi and Xia 1997]. Because of the differences in objectives and constraints, it is important to avoid suboptimization (where each unit works for its own goals without concern for the entire system) and to harmonize and coordinate the actions of the different units and levels [Li and Haimes 1991].

In a highway agency, the decisionmaking hierarchy may consist of three levels: *locality* (local), *district,* and *state.* A combination was developed of the top-down and bottom-up approaches to decisionmaking. The options selected at the asset level must be transmitted up to the different decisionmaking hierarchy levels until the state level is reached. The state makes the overall decision and the resulting resource allocations filter down the hierarchy.

In the developed methodology, the *must* assets are given higher priority in resource allocation and are considered first in the assessment and tradeoff decisions. *Non-must* assets are considered only if funds are still available after the *must* asset allocations have been distributed. Under the hierarchical maintenance structure, the *locality, district,* and *state* levels have different decisions to make. The best asset-maintenance options are promoted to higher levels. Each level has a view across its lower levels which facilitate coordinated decisions to link maintenance projects and derive more economy of scale than is provided in the current decentralized system. With a complete assessment of the maintenance needs at their own level and several options for addressing those needs, decisionmakers can compare the advantages and disadvantages of each option.

The level of asset *locality* is where actual decisions on individual maintenance actions are made and executed. With knowledge of the assets under its supervision, staff members can determine what type of maintenance is needed. The potential maintenance options are enumerated and their costs are estimated. The locality then puts together a maintenance strategy which lists the assets needing maintenance and the options for each asset. The short- and long-term costs for all assets needing maintenance are added. The *remaining life* provides more information for implementing the formulated maintenance strategy. The number of assets that fall into different remaining-life ranges is obtained. This information is used when tradeoff analysis among strategies is conducted. Once the cost values for each maintenance strategy have been aggregated, the locality strategies can be compared directly. The analyst applies experience and judgment to review the resulting list of strategies. Strategies that result in unreasonable outcomes can be removed. For example, the solution where no maintenance is done is technically Pareto optimal, but obviously unacceptable. The locality now possesses a complete assessment of the maintenance needs of its highway assets, and it has several strategies for addressing those needs. The final optimal maintenance strategy sets are passed on to the district level.

The *district* is concerned with the percent of locality asset conditions denoted by *remaining life,* not with specific actions and conditions. Any district-level projects are evaluated using the same process used at the locality level. This paper treats district-level maintenance options in the same way as locality options.

At the level of the *district,* maintenance strategy sets for each of the district's localities are collected and aggregated. The district can evaluate the different maintenance options that comprise the locality strategies and thus learn what actions are planned for specific assets. The district forms several combinations of locality-level strategies; it determines the total short- and long-term costs involved and the remaining asset lives that would result. The analysis provides the district with information on the level of maintenance that can be provided and how much funding is needed to get and keep the highway assets in acceptable condition. When the funding available is already known, only the permutations falling within the budget will be considered in decisionmaking.

The district manager reviews the set of maintenance strategies and the needs of the localities, removes any unreasonable strategies, and performs tradeoff analysis. After the filtration has been completed, the final set of district-level maintenance strategies is passed up to the level of the state.

At the level of the *state,* the maintenance strategy sets from the districts are collected, aggregated, and traded off as described by Figure 6. Two activities can result: resource allocation of available funds to districts, and/or a report to the state about current needs, what can be done with the available budget, and how much can be saved in the long term if more funds are made available now. The maintenance funds available to the state are distributed to the districts as base budget and maintenance funds corresponding to their needs. To arrive at this resource allocation, the same aggregation procedure used at the district level is performed, and different permutations of district-level strategies are developed. The result is a set of statewide maintenance strategies, each with its own short-term cost, long-term cost, and number of assets, with their remaining lives. Each maintenance strategy imp licitly contains a level of funding for each district, locality, and asset. The funds available limit the statewide maintenance strategies. Only strategies that can be met by the available funding are considered, thus reducing the choice of feasible strategies.

If there are sufficient funds to cover the short-term maintenance expenditure for *must* assets, the decisionmaker at the state level has to select from the strategies that fall within the budget. If there are insufficient funds to cover even the critical assets, then the results are useful in justifying the need for more funds, and evaluating the effects a limited budget allocation will have on the condition of the highway system. This analysis provides information on the consequences of the current budget on the level of maintenance and on the amount of maintenance funds that will be needed in the next planning period to keep the highway system functioning according to desired standards.

At the *state* level, decisionmakers consider the budget available and the resulting resource allocations are funneled down to the lower organizational levels. These levels may need to perform additional tradeoff analysis to meet new budget constraints.

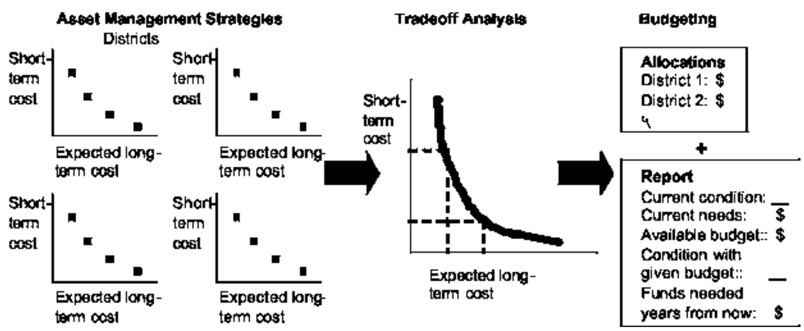


Figure 6. Risk-based analysis at *state* level for maintenance of highway infrastructures resulting in resource allocation and report generation. Tradeoff analysis is performed at all levels.

APPLICATION

The methodology is demonstrated to five one-mile assets listed in Table 4. Two study periods are taken with the length of one study period given to be four years.

Table 4. List of one-mile pavement assets and their corresponding condition indices used to demonstrate risk-based asset management methodology

Asset	Critical Condition Index
A	53
B	53
C	57
D	63
E	89

The maintenance actions for assets A, B, and C are already known and found in Table 5. Therefore, these assets are not carried over to the multiobjective decision tree analysis.

Table 5. Asset management options for assets A, B, and C showing short- and long-term actions, costs, and expected remaining lives

Asset	Option	Short-term Action	Long-term Action	Short-term Cost ($)	Long-term Cost ($)	Short-term Remaining Life (years)	Expected Long-term Remaining Life (years)
A	A-1	Thick overlay	Thin overlay	80000	36700	9. 5	10. 7
B	B-1	Thick overlay	Thin overlay	80000	36700	9. 5	10. 7
C	C-1	Thick overlay	Thin overlay	36700	36700	6. 6	8. 1

Three maintenance options each are considered for assets D and E. Weather affects pavement life, thus two weather scenarios are considered. Normal weather refers to normal snow volume, while severe weather refers to heavy snow volume, or freeze-thaw cycle with snow volume. The probability that a severe-weather year occurs is taken to be 0.1 (1 in 10 years). Multiobjective decision tree analyses are conducted to determine the expected long-term cost, expected short-term remaining life, and expected long-term remaining life. The resulting Pareto optimal options are found in Table 6.

Table 6. Asset management options showing for short- and long-term actions, short-term cost and expected long-term costs, and expected short- and long-term remaining lives of two assets (D and E) that go through multiobjective decision tree analysis

Asset	Option	Short-term Action	Long-term Action		Short-term Cost ($)	Expected Long-term Cost ($)	Expected Short-term Remaining Life (years)	Expected Long-term Remaining Life (years)
			Normal Weather	Severe Weather				
D	D-1	Crack seal	Thick overlay	Slurry seal	1500	65900	3. 5	9. 0
D	D-2	Thick overlay	Chip seal	Slurry seal	80000	5300	4. 2	11. 2
D	D-3	Thick overlay	Microsurface	Thick overlay	80000	26800	10. 9	11. 8
E	E-1	Crack seal	Do nothing	Chip seal	1500	1000	8. 2	9. 3
E	E-2	Crack seal	Crack seal	Crack seal	1500	1500	8. 2	10. 3
E	E-3	Crack seal	Chip seal	Crack seal	1500	4500	8. 2	11. 5

Strategies are generated by considering different combinations of options for all five assets. The strategies are identified in Table 7.

Table 7. Example of *locality*-level strategies that result by looking at various permutations of asset-level options for all assets (A through E)

Locality Strategy	Locality Asset Options
1	A-1, B-1, C-1, D-1, E-1
2	A-1, B-1, C-1, D-1, E-2
3	A-1, B-1, C-1, D-1, E-3
4	A-1, B-1, C-1, D-2, E-1
5	A-1, B-1, C-1, D-2, E-2
6	A-1, B-1, C-1, D-2, E-3
7	A-1, B-1, C-1, D-3, E-1
8	A-1, B-1, C-1, D-3, E-2
9	A-1, B-1, C-1, D-3, E-3

The short-term costs and expected long-term costs for each strategy are obtained, and the number of assets found in each expected remaining life range is counted. The costs and expected remaining life information for each locality-level strategy are shown in Table 8.

Table 8. Examples of strategies at the *locality* level showing total short- and expected total long-term costs, and the distribution of assets according to remaining life

Locality Strategy	Total Short-term Cost ($)	Expected Total Long term Cost ($)	Number of Assets in Each Expected Remaining Life Range			
			1 – 3 years	4 – 6 years	7 – 9 years	10 – 12 years
1	199700	177000	0	0	3	2
2	199700	177500	0	0	2	3
3	199700	180500	0	0	2	3
4	278200	116400	0	0	2	3
5	278200	116900	0	0	1	4
6	278200	119900	0	0	1	4
7	278200	137900	0	0	2	3
8	278200	138400	0	0	1	4
9	278200	141400	0	0	1	4

It can be seen in Figure 7 that the locality-level strategies have three clusters according to their total short- and expected total long-term costs. The *locality* then selects a set of strategies to send to the *district.* Specifically, tradeoffs are made among the total short-term costs, expected total long-term costs, and the expected remaining life. In general, the decisionmaker has to use his experiential knowledge in choosing the candidates for higher-level aggregation.

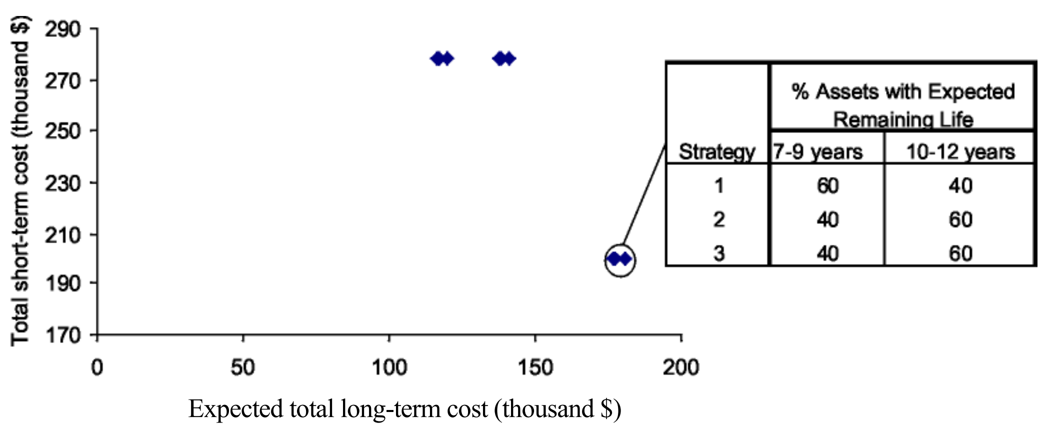


Figure 7. Example of a summary report showing tradeoffs in terms of total short- and expected total long-term costs, and distribution of assets according to remaining life for strategies at the *locality* level

The same procedure is followed to deal with five one-mile assets from two other localities. The strategies from three localities are then submitted to the district. The submitted strategies are found in Table 9. The district now has the ability to compare projects across localities.

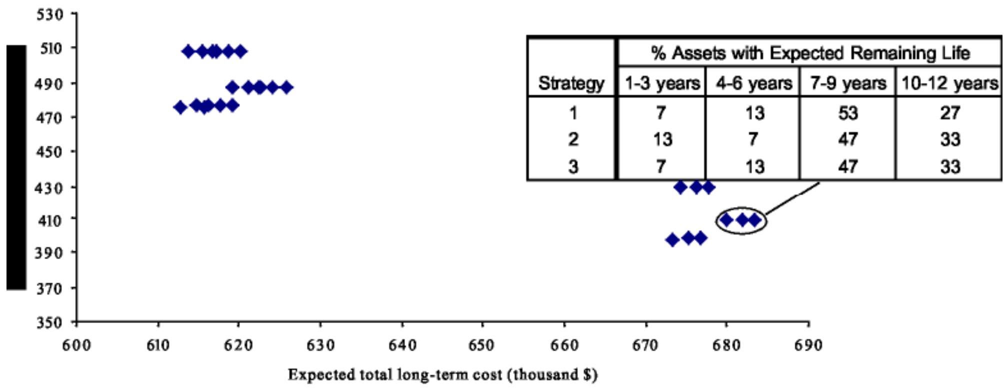
Table 9. Examples of strategies submitted to the district showing locality strategies, total short- and expected total long-term costs, and distribution of assets according to remaining life

Locality	Locality Strategy	Total Short-term Cost ($)	Expected Total Long term Cost ($)	Number of Assets in Each Remaining Life Range			
				1 – 3 years	4 – 6 years	7 – 9 years	10 – 12 years
1	1	115200	23300	1	1	3	0
1	6	125800	29800	1	1	3	0
1	7	146700	24200	1	1	3	0
2	2	199700	177500	0	0	2	3
2	5	278200	116900	0	0	1	4
2	6	278200	119900	0	0	1	4
3	2	83000	474500	0	1	3	1
3	4	82800	472600	1	0	2	2
3	6	83000	476000	0	1	2	2

The *district* aggregates these locality strategies by considering different permutations. The total short- and expected long-term maintenance costs are obtained and additional information on the district strategies is provided by knowledge of the assets' remaining lives. A sample of the aggregated information is found in Table 10. The strategies shown in Figure 8 exhibit some degree of clustering. Thus, the decisionmaker can decide on which cluster to investigate more deeply and can perform tradeoff analysis among the objectives of minimizing short-term cost, minimizing long-term cost, and harmonizing the remaining lives across assets.

Table 10. Examples of strategies at the *district*-level showing the locality strategies, total short- and expected total long-term costs, and distribution of assets according to remaining life

District Strategy	Locality Strategy			Total Short-term Cost ($)	Expected Total Long-term Cost ($)		Number Remaining	of Assets in Each	
	Loc. 1	Loc. 2	Loc. 3			1 – 3 years	4 – 6 years	7 – 9 years	10 – 12 years
1	1	2	2	397900	675300	1	2	8	4
2	1	2	4	397700	673400	2	1	7	5
3	1	2	6	397900	676800	1	2	7	5
4	1	5	2	476400	614700	1	2	7	5
5	1	5	4	476200	612800	2	1	6	6
6	1	5	6	476400	616200	1	2	6	6
7	1	6	2	476400	617700	1	2	7	5
8	1	6	4	476200	615800	2	1	6	6
9	1	6	6	476400	619200	1	2	6	6
10	6	2	2	408500	681800	1	2	8	4



Strategy	% Assets with Expected Remaining Life			
	1-3 years	4-6 years	7-9 years	10-12 years
1	7	13	53	27
2	13	7	47	33
3	7	13	47	33

Figure 8. Example of a summary report showing tradeoffs in terms of total short- and expected total long-term costs, and distribution of assets according to remaining life for strategies at the *district* level

The strategies from the various districts are submitted to the *state* level where aggregation of the district-level strategies is performed by considering different permutations. The total short- and expected total long-term maintenance costs are obtained and additional information on the strategies is gained by considering the assets' expected remaining lives. The *state* can review across districts to make informed decisions about the allocation of available funds. The state administrator can select from the list of Pareto optimal strategies. Given certain funding allocations to the various districts, the state administrator knows the distribution of asset conditions (expressed in remaining lives) that can be expected.

SUMMARY

The developed asset management methodology serves as a decisionmaking tool for highway planners and maintenance engineers. This paper presents a risk-based methodology that offers meaningful and measurable tradeoffs among risks, costs, and benefits for asset management. The innovative process filters and assesses assets for maintenance while incorporating the potential for extreme events. This extension is a specialization of the Risk Filtering, Ranking, and Management methodology by Haimes et al. [2002]. The framework distinguishes *now* from *later* by using multiobjective decision tree analysis to demonstrate the tradeoffs between long-term and short-term costs, and remaining life.

The features of the methodology are:

- Considers uncertainty brought about by weather to the asset condition, expressed as remaining life.
- Can be used at each level of the highway infrastructure hierarchy to perform tradeoff analysis with information passed on in a standardized format.
- Provides comprehensive information coupled with use of existing databases.

- Provides a process with which to perform comparisons across assets by using common criteria and measures. Maintenance costs can be directly compared. Since remaining life is expressed as a function of asset condition, the different remaining lives of assets can be used to harmonize maintenance activities across assets.

- Enables managers to support their decisions with quantitative analysis based on engineering evidence.

- Provides decisionmakers with a full set of maintenance options with quantified consequences of various strategies.

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