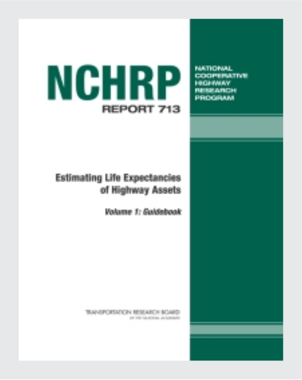

Estimating Life Expectancies of Highway Assets, Volume 1: Guidebook

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 713

Estimating Life Expectancies of Highway Assets

Volume 1: Guidebook

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Andrew C. Lemer
Staff Officer
Transportation Research Board

This two-volume report provides a methodology for estimating the life expectancies of major types of highway system assets, in a form useful to state departments of transportation (DOTs) and others, for use in lifecycle cost analyses that support management decision making. Volume 1 is a guidebook for applying the methodology in DOT asset management policies and programs. Volume 2 describes the technical issues and data needs associated with estimating asset life expectancies and the practices used in a number of fields—such as the energy and financial industries—to make such estimates.

The deterioration of highway infrastructure begins as soon as it is put into service. Effective management of highway system assets requires a good understanding of the life expectancy of each asset. Asset life expectancy is the length of time until the asset must be retired, replaced, or removed from service. Determining when an asset reaches the end of its service life generally entails consideration of the cost and effectiveness of repair and maintenance actions that might be taken to further extend the asset's life expectancy. Different types of assets, such as pavements, bridges, signs, and signals, will have very different life expectancies. Asset life expectancy also depends on the materials used; demands actually placed on the asset in use; environmental conditions; and maintenance, preservation, and rehabilitation activities performed.

Effective management of highway system assets requires that agency decision makers design and execute programs that maintain or extend the life of the various types of assets in the system at low cost. Designers use estimates of asset life expectancy in their lifecycle cost analyses to make design decisions, but those estimates depend on assumptions about maintenance practices, materials quality, service conditions, and characteristics of the asset's use. If actual service conditions and maintenance activities subsequently differ from the designer's assumptions, the asset's life is likely to be different from initial estimates. Better information and tools for estimating asset life expectancies are needed to guide in-service asset management programs. Research is needed to determine the life expectancies of assets for at least four potential cases: (1) when maintenance and preservation activities are performed as assumed by the designer in the lifecycle cost analysis, (2) when little or no maintenance is performed over the life of the asset, (3) when more aggressive maintenance and preservation activities are performed to extend the asset's life, and (4) when materials or designs that require no or very little maintenance are used.

The objectives of NCHRP Project 8-71 were to (1) develop a methodology for determining the life expectancies of major types of highway system assets for use in lifecycle cost analyses that support management decision making; (2) demonstrate the methodology's use for at least three asset classes, including pavement or bridges and two others, such as culverts, signs, or signals; and (3) develop a guidebook and resources for use by state DOTs and others for applying the methodology to develop highway maintenance and preservation programs and assess the effect of such programs on system performance.

A research team led by Purdue University, West Lafayette, Indiana, conducted the research. The project entailed a review of current literature and practices within highway agencies and other industries, such as utilities and vehicle- and equipment-fleet management, to describe the methodologies currently used to determine life expectancy for major assets. The research team considered both new and in-service highway assets (such as pavements, bridges, culverts, signs, pavement markings, guardrail, and roadside facilities), and described the factors likely to influence predicted or assumed asset life expectancies. These factors include materials, design criteria, construction quality control, and maintenance policies and practices. Data needs and availability influence analytical ability to estimate and predict asset life expectancies. Geographic location and highway system management policies also influence life expectancies. Considering these factors, the research team described methodologies for estimating the life expectancy of major types of highway system assets, for use in lifecycle cost analyses that support maintenance and preservation management decision making.

The research produced this two-volume report. Volume 1 is a guidebook designed to be used by transportation agency staff wishing to estimate asset life expectancies. The guide will be useful to agency staff and their advisors in developing asset management and maintenance systems, policies, and programs. Volume 2 documents the research project and presents background information and research results that will be useful to other researchers and practitioners wishing to know more about the theories and methods for estimating asset life expectancies.

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

CHAPTER 1

Introduction: How to Use This Guide

The deterioration of highway infrastructure begins as soon as it is put into service. Effective management of highway system assets requires a good understanding of the causes and rates of deterioration and the ultimate life expectancy of each asset.

Asset life expectancy is generally defined as the length of time until the asset must be retired, replaced, or removed from service. Determining when an asset reaches the end of its life entails consideration of the repair and maintenance actions that might be taken to further extend its life. Different types of assets, such as pavements, bridges, signs, and signals, will have very different life expectancies. Asset life expectancy also depends on the materials used; the demands actually placed on the asset in use; the environmental conditions; and the maintenance, preservation, and rehabilitation activities performed.

Effective management of highway system assets requires that agency decisionmakers design and execute programs that maintain or extend the life of the various types of assets in the system at low cost. Designers use estimates of asset life expectancy in their lifecycle cost analysis to make design decisions, but those estimates depend on assumptions about maintenance practices, material quality, service conditions, and characteristics of the asset's use. If actual service conditions and maintenance activities subsequently differ from the designer's assumptions, the asset's life is likely to be different from initial estimates.

The ability to forecast life expectancy is one part of a larger set of tools that agencies need in order to advance the maturity of their asset management business processes. Forecasting tools equip an agency to be proactive and to actively intervene in the asset lifecycle to optimize future cost and performance. This is in contrast to a less mature process where decisions are based on reacting to conditions and problems which have already taken place.

Proactive decision-making requires that an agency have credible models for future deterioration, future maintenance requirements, and future replacement of assets. Along with quality analysis methods, agencies require functional data, clear communication methods, and a confident implementation process in order to earn the buy-in of stakeholders for this more far-sighted mode of decision-making. In addition, successful implementation requires flexibility in the establishment of performance standards, accountability for those standards, and innovation in delivery capabilities, all of which provide the agency with more options for satisfying the diverse needs of stakeholders.

This guide gives decisionmakers, practitioners, and stakeholders an actionable cookbook and authoritative reference on the uses of life expectancy analysis, its benefits and limitations, and its data sources and products. This guide describes current methods for various types of infrastructure, from pavements and bridges to signs and signals. To help practitioners get started, the guide is presented in a "how to" format with realistic examples and a number of sample spreadsheet models. More broadly, the guide is framed with a vision of asset management implementation, consistent with AASHTO guidance, which will help senior managers to understand why they should implement the guide, what they should expect, and how to begin.

1.1 Who Should Use This Guide

Preservation of infrastructure assets is a matter of concern to all facility owners, public and private. This guide, with its focus on transportation assets, is especially intended for public owners of transportation facilities at all levels of government. The methods in the guide are applicable to inventories of all sizes, for centralized or decentralized organizations, and address all the individual asset management phases: planning, programming, project development, maintenance and operation, and disposal.

Asset management is fundamentally a cooperative effort among all levels of an organization and its external stakeholders. One of the primary purposes of asset management is to help these diverse actors to cooperate and work effectively to improve the level of service delivered to customers. This guide therefore has specific sections for the different levels of involvement.

Specifically

- Senior managers and outside stakeholders will acquire a top-down vision of what life expectancy really means for decision-making and how life expectancy fits in the process of selecting and budgeting for projects and in the management of routine maintenance (Chapters 1 and 2).
- Oversight bodies and managers will gain tools for converting the vague and informal concept of asset life into something that can actually be measured and used for planning, performance tracking, and accountability (Chapters 2 and 3).
- Asset managers will gain insight to using life expectancy as a performance measure for routine decision-making processes (Chapter 3).
- Practitioners will learn how to compute life expectancy and related measures, how to obtain the necessary data, how to reconcile such data with other measures of asset performance, and how to present such material to decisionmakers (Chapters 3, 4, and 5).
- Engineers and maintenance planners in the traditional disciplinary and modal roles in transportation agencies will learn how the concepts of life expectancy that they often use can be quantified in a way that is more objective and more compatible with other disciplines and roles in the agency (Chapters 4 and 5).
- System designers will learn how to incorporate life expectancy performance measures into management system software and tools (Chapters 5 and 6).
- Researchers will find opportunities to continue improving the state of the practice in asset life studies (Chapter 6).
- Senior managers will see how to ensure the long-term perpetuation of mature asset management practices using life expectancy tools (Chapter 7).

Figure 1-1, which presents the participants and groups that have roles in asset management, is reproduced from the *AASHTO Transportation Asset Management Guide, Volume 2: Focus on Implementation* (Gordon et al. 2010). All of the players in asset management have a potential interest in asset life expectancy as one of the tools they may want to have at their disposal. This guide frequently refers to the *AASHTO Transportation Asset Management Guide* as the organizing framework for implementation of the tools described here.

It is important that the values of life expectancy are calculated in a manner that is objective, quantitative, and relevant to agency responsibilities and objectives, and as precise and accurate as possible with available data. Like most other asset management inputs, the true value of life expectancy is more than just the success of calculating it. The value lies in the ability to use it to

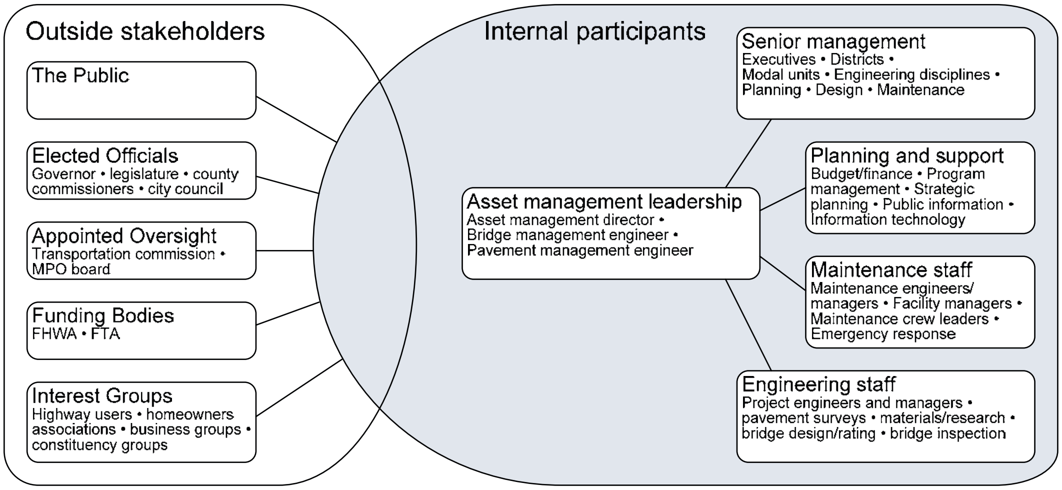


Figure 1-1. Organizational roles in asset management *(Gordon et al. 2010).*

gain agreement across the agency and with stakeholders on the agency's objectives, the rationale for resource allocation decisions, the process of satisfying objectives and in determining whether they have been satisfied, and the fairness of the agency's accountability measures.

1.2 Setting Goals and Objectives

Calculation of life expectancy can be a fairly esoteric pursuit unless the agency has a clear idea of how it wants to use the information. Before trying to implement the analytical methods, it is helpful to list the goals and objectives of those initiating the effort and the agency's objectives in embracing it. Possible asset management goals include

- Justifying funding for preventive maintenance.
- Planning and justifying the timing and scope of rehabilitation and replacement.
- Planning sufficient staffing and equipment to meet maintenance needs.
- Setting desired inventory levels for parts and materials.
- Evaluating the cost-effectiveness of new materials or methods.
- Reducing the overall frequency of highway rehabilitation and maintenance work zones.
- Improving the consistency of accounting reports.
- Optimizing the terms of bond issues.
- Improving management guidance and accountability.
- Building credibility with oversight bodies and elected officials.

Many of these objectives address an agency's need to minimize the cost of providing the desired level of service to customers. Some also respond to non-economic needs such as improving the safety of the public and maintenance crews, enhancing management professionalism, and reducing risk. Although goal statements are often broad, they provide a foundation for ensuring that the right measures are computed and that the applications of life expectancy analysis are relevant to an agency's needs and capabilities.

1.3 Listing Desired Applications

This guide is meant to be a practical tool that agencies can use immediately to enhance asset management processes. A recurring theme is the contributing role that life expectancy analysis can have when used as a part of a larger transportation asset management plan. Assumptions about asset lifespan are built into various design and maintenance tools and procedures. Predictions of asset life extension form a part of the justification for various maintenance, repair, and rehabilitation projects, programs, budgets, and policies.

Figure 1-2 shows the role of life expectancy analysis superimposed over a model of asset management business processes. The diagram illustrates how life expectancy estimation is built on the products of the research and data collection processes of an agency; and in turn, life expectancy analysis contributes directly to preservation policy formation, project development, and preservation needs assessment, largely through use as a performance measure for quantifying the effects of agency decisions. Less directly, the expectations of an agency's designated asset lifespans affect the design of certain information systems and their analyses, as well as the assumptions that are made in financial decisions such as debt terms, depreciation, amortization, and cash flow.

Further, through its use in preservation policy and planning, asset life expectancy indirectly affects the processes of budgeting, network planning, corridor development, design, and maintenance planning. Agencies increasingly seek to adopt design and construction methods that minimize future maintenance requirements or that facilitate coordination of preservation activities across asset categories in a corridor or region. Such decisions can reduce traffic disruptions, improve economies of scale, and reduce the indirect costs (mobilization and traffic control, for example) of activities. Given that life expectancy analysis touches so many routine business processes, this guide will provide various example applications, such as

- Estimating life expectancy when little or no maintenance is performed.
- Estimating life expectancy when preservation work is performed according to an established policy, such as the policy established by a facility designer, current agency policy, or proposed future agency policy.
- Estimating the life-extension effects of preventive maintenance activities on constructed facilities such as pavements and bridges.
- Comparing two or more alternative maintenance, repair, and rehabilitation alternatives on a facility, under differing assumptions and discount rates.
- Determining the optimal replacement interval for expendable assets and components.
- Determining the optimal preventive maintenance interval for constructed facilities.
- Determining the optimal annual expenditure level on periodic maintenance activities.
- Optimizing life extension to select the best scope and timing of preservation work on constructed facilities.
- Comparing design alternatives based on their relative lifecycle costs; for example, comparing a conventional material with a more expensive low-maintenance material.
- Determining the price point where a low-maintenance material becomes cost-effective.
- Proactively grouping future preservation work on multiple assets into projects based on the anticipated convergence of their end-of-life conditions.
- Selecting design alternatives for the various assets on a corridor, such that preservation and replacement interventions likely can be synchronized and long-term traffic disruptions can be minimized.
- Multi-objective prioritization of programmed projects, using life extension as one of the criteria.
- Allocating funding among investment categories using asset life extension in a multi-objective framework.
- Determining the effect on asset life and long-term costs for variations in near-term funding levels.
- Selecting treatment application policies based on rate of return, using life extension and lifecycle cost forecasts in the computation.
- Computing life expectancy as a by-product of a decision simulation, such as what is done in a pavement or bridge management system.
- Establishing research priorities for improved lifespans of certain types of assets.
- Establishing a rate of depreciation for GASB 34 financial analysis.

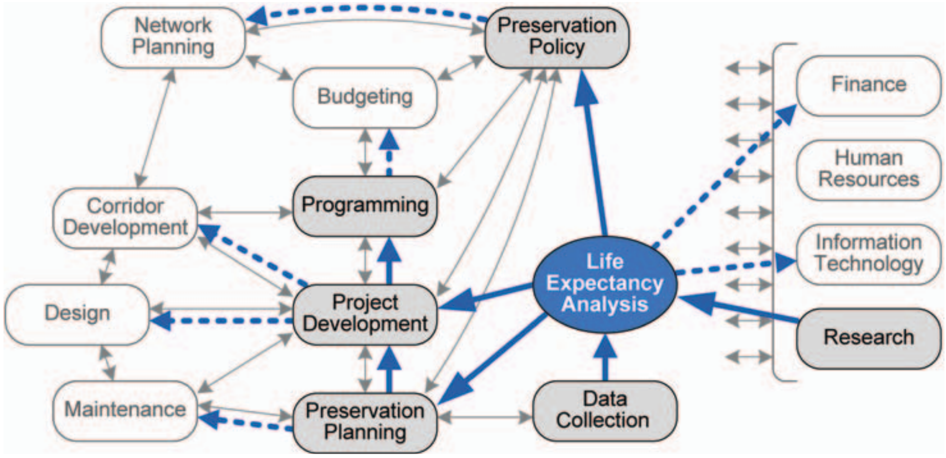


Figure 1-2. How life expectancy analysis affects business processes.

Chapters 4 and 5 of this guide will provide approaches and examples for most of these applications, which can be used by agencies to visualize how to put the techniques to work and which may be considered prototypes for applications and systems that the agency may want to develop as it gains more sophistication in asset management.

1.4 Delimiting the Scope of the Effort

It is tempting to think that an analytical tool, once developed, can be applied to any type of asset in any part of an agency's network. Practical realities, however, preclude this from happening. Agencies often find it convenient to start with the portions of their asset inventory where there is already a strong practice in the collection and use of data; for example, bridges or pavements in the state highway system. Many agencies have established excellent databases, mature quality assurance functions, and a quantitative management culture for certain asset types.

Once the application scope is expanded to cover a wider range of asset types, implementation may become more difficult because data may be absent or incomplete. If certain data have not been in routine use for important agency functions, their quality may never have been tested or may be doubtful. Sufficient personnel may not be available to gather or process the necessary data. In such cases, a history of performance measurement or performance accountability may be absent; and certain parts of the transportation system or asset inventory may not have sufficient weight, in cost or performance, to justify a detailed analysis.

One frequently repeated piece of good advice in asset management applications is to "start small, build incrementally" (Figure 1-3). Often, life expectancy analysis, or the related topic of lifecycle cost analysis, is the first and only truly quantitative asset management tool that an agency has tried to put in place for asset management. If this is the case, obstacles related to inertia, culture, and custom may arise. An implementation effort that faces the barriers of requiring considerable time and resources may never be able to succeed.

To help in applying new analytical tools within a selected scope in an agency, AASHTO's transportation asset management guides describe various strategies and tactics to help overcome resistance. In terms of the scoping of an implementation effort, a key strategy is to plan to show early useful results, for only a portion of the asset inventory. Such early results should be based on data the agency already has, or can obtain easily, whose quality is at least minimally acceptable. The analysis may be simpler than what is eventually desired, a "back of the envelope" exercise,

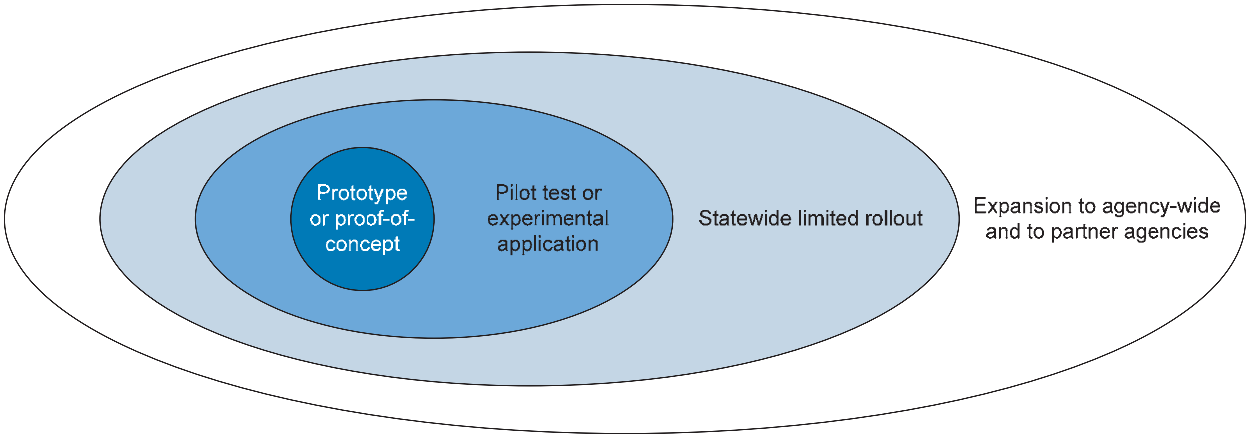


Figure 1-3. Start small, build incrementally.

for example. The early product should be attractive and persuasive and should address an immediate need, even if only a part of the need.

As a result, the initial application of analysis tools, such as life expectancy estimation techniques, often may be limited to the state highway system or even to only one district that is willing to experiment or innovate. Application may be limited to assets where the agency already has data, such as the bridge inventory or the Federal Highway Performance Monitoring System (HPMS) dataset, or may rely on data from manufacturers or other agencies (Figure 1-4).

In any event, the scoping strategy will often have multiple levels, envisioning expansion over time. It is important that stakeholders understand the current scope and the desired future scope, as well as the barriers, costs, and benefits that will occur as the tools are expanded.

1.5 Assessing Gaps and Readiness

A new methodology such as life expectancy analysis arrives in an agency that likely already has its ongoing processes of asset management underway. Many of the goals and objectives suggested in the preceding sections are aspects of using the new tools to improve current asset management processes. But life expectancy methods can range from very simple to very

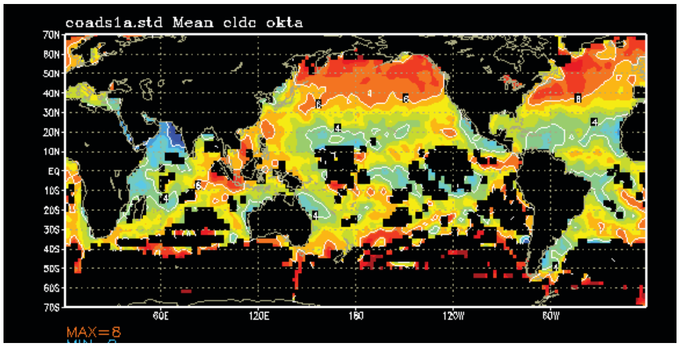


***Figure 1-4. NOAA can be an excellent source of climate data** (http://www.esrl.noaa.gov/psd/products/images/search.gif).*

sophisticated. So it is important to ask at the beginning of the effort: In what ways do we need to improve next? How much improvement can we sustainably accomplish in one step? How much change can we absorb?

Volumes 1 and 2 of the *AASHTO Transportation Asset Management Guide* (Cambridge et al. 2002, Gordon et al. 2010) describe the processes of self-assessment and gap analysis that provide strategic and tactical guidance to help answer these questions. The process is based on the concept of a "maturity scale," which provides location and orientation in a model of agency advancement.

> The maturity scale is not a value judgment: it does not separate "good" organizations from "bad" ones. Every agency is on a journey toward improved asset management, and the maturity scale provides the "you are here" marker on a map of that journey (Gordon et al. 2010).

Table 1-1 summarizes the maturity scale, levels, and descriptions. Advancement on the scale involves the following:

1. Increasing the level of cooperation vertically and horizontally among the units of the organization,
2. Increasing the shared understanding of agency objectives and constraints across the agency and with its customers and stakeholders,
3. Increasing the use of quantitative measures of performance,
4. Being more proactive in using agency decisions and actions to improve future performance,
5. Using performance measurement for accountability,
6. Gaining more effective support from decision support tools, and
7. Increasing the drive among all employees to improve the agency's performance.

The self-assessment can be conducted using a survey of agency personnel, either formal or informal. It might not be necessary to conduct a survey specifically related to life expectancy analysis if the agency is already using this process for asset management in general.

The stages of maturity tend to move together across the full breadth of asset management. For example, it would be unusual to be successful in implementing sophisticated optimization of bridge preservation over its lifecycle at the same time as lacking a basic complete pavement database. Similarly, the standardization of life expectancy definitions across asset types may be difficult if management has not already made efforts to increase communications and teamwork across organizational silos. In both cases, the difficulty lies in the fact that to make a new analysis technique successful, it is necessary to increase the demand for the information as well as the supply.

Table 1-1. Transportation asset management maturity scale (Gordon et al. 2010).

Maturity Level	Generalized Description
Initial	No effective support from strategy, processes, or tools. There can be lack of motivation to improve.
Awakening	Recognition of a need and basic data collection. There is often reliance on heroic effort of individuals.
Structured	Shared understanding, motivation, and coordination. Development of processes and tools.
Proficient	Expectations and accountability drawn from asset management strategy, processes, and tools.
Best Practice	Asset management strategies, processes, and tools are routinely evaluated and improved.

Table 1-2 lists the kinds of questions that a maturity scale survey would address. These include both technical and non-technical subject matter, the use of information as well as the ability to produce and manage it.

1.6 How to Use This Guide

There are various ways of computing life expectancy, depending on the planned use of the information, assumptions about how end-of-life is defined, and the types of policies to which the method must be sensitive. A great many of these methods have engineering or economic validity, but successful implementation often depends on acceptance by people who are not engineers or economists and has to be compatible with agency history and accountability.

If this guide is to facilitate successful implementation, then it must aid in understanding the context in which the information is needed so as to ensure that the right kind of life expectancy calculation is performed for a given set of applications in a given agency with its current policy concerns and current state of maturity.

This sensitivity to decision context is a great concern throughout asset management and is a recurring theme in the AASHTO *Transportation Asset Management Guide*. Figure 1-5, reproduced from Volume 2 of the AASHTO Guide, shows the approach taken in order to ensure that the selection and adoption of analytical tools is properly fitted to the agency context, to ensure that the investment in better tools pays off with sustained implementation. Typically the tools of life expectancy estimation fall within Step 11, Lifecycle management, in the diagram.

This guide is designed to fit into the AASHTO Transportation Asset Management framework so as to maximize the likelihood of implementation success. As a result, this guide is organized in a top-down fashion: defining first the purpose and implementation plan for the techniques, then defining stakeholder needs for the information, and finally using this insight to select the right tools for the job and designing them so they work correctly and as expected.

Figure 1-6 shows the recommended process of planning, selection, and implementation of life expectancy tools and describes the structure of this guide. Thus each chapter in the guide

Table 1-2. Relevant topics for self-assessment (Cambridge et al. 2002).

Part A. Policy Guidance *How does policy guidance benefit from improved asset management practice?*
Policy guidance benefitting from good asset management practice Strong framework for performance-based resource allocation Proactive role in policy formulation
Part B. Planning and Programming *Do resource allocation decisions reflect good practice in asset management?*
Consideration of alternatives in planning and programming Performance-based planning and a clear linkage among policy, planning and programming Performance-based programming processes
Part C. Program Delivery *Do program delivery processes reflect industry good practices?*
Consideration of alternative project delivery mechanisms Effective program management Cost tracking and estimating
Part D. Information and Analysis *Do information resources effectively support asset management policies and decisions?*
Effective and efficient data collection Information integration and access Use of decision support tools System monitoring and feedback

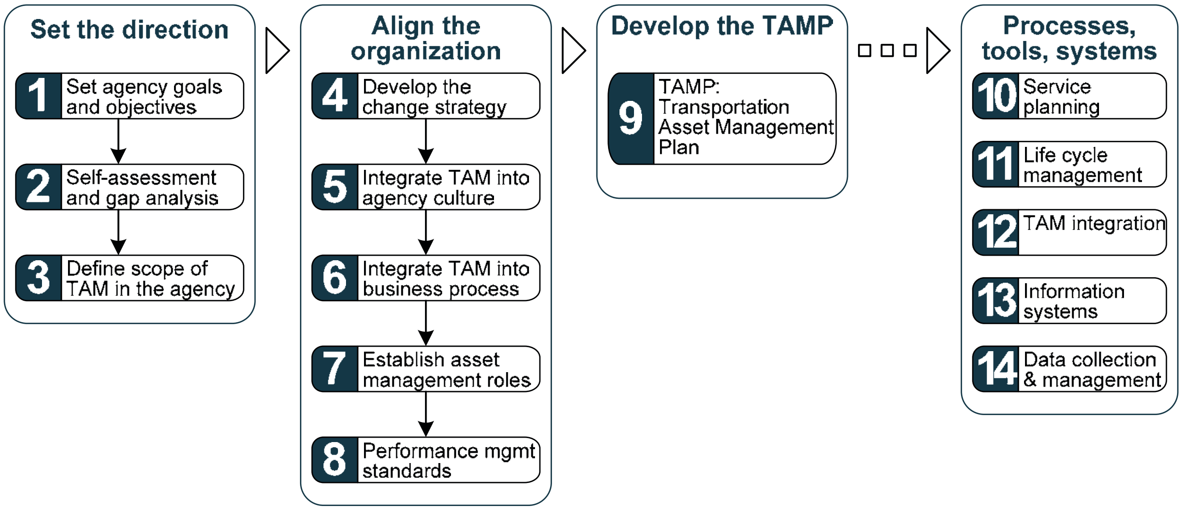


Figure 1-5. Road map for asset management implementation *(Gordon et al. 2010).*

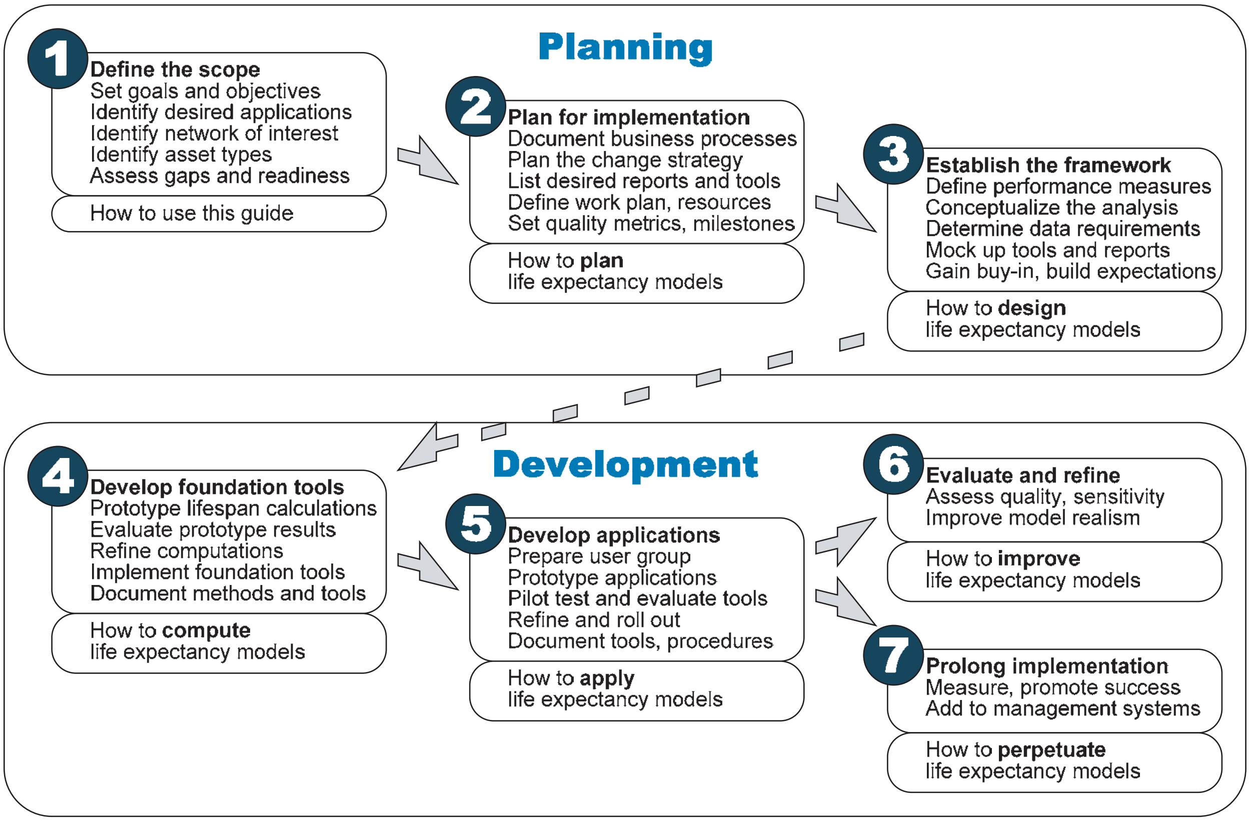


Figure 1-6. Structure of implementation and of this Guide.

corresponds to an implementation step, consisting of several tasks. Each step also corresponds to a step in the development of the life expectancy computations.

Chapters 1 through 3 focus on understanding how the life expectancy estimation methods will be used and learning how to use this planning information to select the right tools and the right level of detail. Senior managers and stakeholders can use the material in these chapters to decide what life expectancy information to ask for, what the agency has to do in order to get the information on a reliable and cost-effective basis, and how to use the information to improve decision-making.

The high-level, relatively non-technical information in Chapters 1 through 3 is then followed by a progressively more technical presentation in Chapters 4 through 6, where life expectancy methods are described in detail and reinforced with examples. If Steps 2 and 3 of the process determine what is to be computed, then Step 4 is where the basic computation of asset life expectancy actually takes place. This step is where the end-of-life is determined quantitatively for each asset, deterioration and future performance are forecast, and a determination is made as to how many years it will take for each asset to meet its end-of-life criterion.

Once the foundation tools are in place to compute life expectancy, then Step 5 puts the information to work to assist in answering practical asset management questions. As already emphasized, an agency may have a great many questions and decision-making tasks where the new information can be put to use.

Although Chapters 4 and 5 are fairly detailed, the reader does not have to read all of it. The self-assessment and gap analysis in Step 1 and the requirements analysis and planning in Steps 2 and 3 will help the agency to select the specific methods that it should implement. So for each given agency at a given point in time, only selected portions of Chapters 4 and 5 will be relevant.

Finally, as agencies become more mature in their asset management capabilities, Steps 6 and 7 become more relevant. In these steps, the agency ensures that its implementation of life expectancy tools is sustainable, evaluates these tools more critically, and seeks ways to improve them. The topics in Chapter 6 cover what are considered to be “best practices” in asset management for continuously evaluating and improving the models. Chapter 7 involves taking the necessary organizational steps to make sure the applications will become a permanent part of the agency’s business processes, to ensure sustained asset performance, and to provide the greatest possible returns to customers and stakeholders.

CHAPTER 2

Plan for Implementation: How to Plan Life Expectancy Models

When implementing any kind of decision support tool, good planning goes a long way to ensure that the tool will produce information that is reliable, useful, and relevant. It is easy, and all too common, to develop models that have considerable engineering and economic merit, but whose outputs never affect the management and political decisions that determine how money is allocated. It is therefore useful to list the benefits of transportation asset management. Reasons why senior management would be interested in the products of analytical tools such as life expectancy analysis include the following:

- Credible long-term view. If procedures are in place to ensure that the inputs and analysis are routinely tested, adjusted, and validated to agree with real life, the life expectancy analysis can provide a useful and politically neutral way of comparing alternative policies and programs having long-term impacts.
- Basis for transparency and accountability. Credible performance measures help all stakeholders to verify that promised project benefits are actually realized.
- Means to specify the desired level of service. While the general relationship between funding and performance is widely appreciated but vaguely understood, the use of quantitative performance measures makes it possible to specify precisely how much performance is wanted and can be afforded.
- A way to isolate the effects of traffic/demand growth and deterioration. Analysis tools such as life expectancy analysis help agencies and stakeholders understand the long-term investments necessary to maintain a desired level of service in the face of traffic growth and deterioration.
- Maximize the benefits of infrastructure preservation. The ability to proactively estimate the effects of investments assists managers in balancing resource allocation to maximize network-wide performance delivered to all transportation system users.
- Improve agency competitiveness for funding. Credible analytical tools give senior managers a competitive technique to use in funding negotiations.
- Build constructive political relationships. Performance measures such as life expectancy provide a common language for communication and provide a basis for managers and outside stakeholders to work as a team to address deterioration and traffic growth, to best serve the needs of their shared customers.

The planning process described in this chapter is condensed from the much more detailed presentation in the AASHTO *Transportation Asset Management Guide* (Gordon et al. 2010). By understanding the motivations of senior managers and stakeholders, the implementer of life expectancy analysis tools is in a better position to select and design business processes and analysis methods that will ensure that the results are credible and useful.

2.1 Documenting Business Processes

Often the demand for analysis techniques originates with a single person or organizational unit that needs the information, but fulfillment of that demand necessitates the cooperation of many others in the organization who (1) might not understand whether or not they would benefit and (2) are already engaged in important duties. One of the most important implications of this insight is that all of the business units that might use the information are potential beneficiaries and potential allies in advocating for the use of a new analytical tool and the accompanying change and improvement.

A productive way to improve implementation success is to systematically identify the potential partners, using a business process analysis (Jacobson 1995). Figure 2-1 shows an example. The idea is to show all the activities that the agency undertakes that either may benefit from life expectancy information or that affect the quality of the information and then to connect the boxes with data flows that are potentially relevant. This need not be a formal undertaking, but it does have strategic importance by indicating the people who could help or hinder implementation success and then guiding the preparation of the list of desired reports and tools.

In a corporate environment, it is not unusual for an analytically inclined engineer to team with a people-oriented product manager to secure the necessary support and resources. A diagram like Figure 2-1, a map of the contacts that need to be made, might be drawn on a napkin or written into a memorandum. By following the connecting lines, it is easy to trace the flows of data and see how better information can be available to each player and affect his or her decision-making.

2.2 Planning the Change Strategy

Implementation of asset management tools, such as life expectancy estimation techniques, is a process of change. In an organization, change can be viewed with apprehension or with opposition. It is important to recognize that change can have both positive and negative effects on each

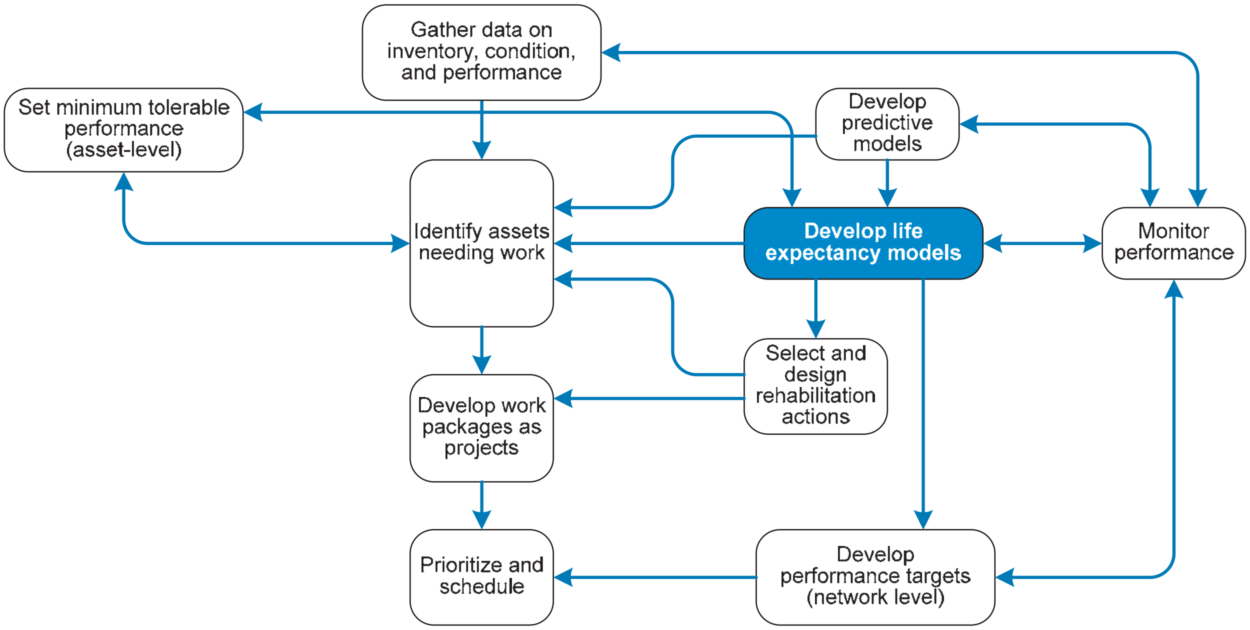


Figure 2-1. Example business process analysis.

employee. Change management is often a process of engineering the effects of the change so that, from each person's perspective, the positive outweighs the negative. Improved asset management information often implies increased accountability, which can be especially alarming. Change leaders have to be especially sensitive to these fears and actively try to mitigate them.

Successful organizational change to accommodate the new life expectancy estimation tool would require at a minimum the following activities (Gordon et al. 2010):

- Convince employees of the need for and benefits of the change. For senior managers, the list at the beginning of this chapter is a helpful starting point.
- Create a change leadership coalition, consisting of people who may benefit from the change and can articulate the benefit to the agency or the customer. Share the leadership duties and encourage creative input, even constructive disruption.
- Develop a vision of the end result after the changes and the strategy needed to get there.
- Communicate the vision regularly.
- Take actions consistent with the vision.
- Ensure that people are involved and are empowered to make changes consistent with the vision.
- Reinforce the change effort with short-term successes.
- Keep the focus on the change effort.
- Anchor new approaches into the culture.

Successful change is incremental and measured. If implementation of the life expectancy estimation tool is a part of process changes in the organization, as often will be the case, the user of this guide should follow the steps presented in Chapter 1 to determine where to start and how far to go with the implementation process. Each increment of change depends on the successful completion of the previous round of changes, with sufficient time allowed for the new capabilities and thought processes to sink into the culture. An agency in a relatively immature state of asset management may require several years to implement all the techniques described in this guide.

2.3 Listing Desired Reports and Tools

The logical sequence of events in planning a life expectancy modeling capability change follows a natural pattern, from general goals to a specific work plan (Figure 2-2). It is important to follow such a plan, rather than jumping directly to writing a spreadsheet or computer code. Such a plan ensures that the product will be relevant to as many people as possible in the agency and that the product will be valuable and used.

Once the potential users and business processes are identified and the desired applications documented, it becomes possible to make a more specific list of the tools needed. At first, it is very likely that the most relevant tools will be spreadsheet models, which feed off of one or more asset management databases. For agencies lacking inventory and condition databases for certain types of assets, the first tools will likely involve databases.

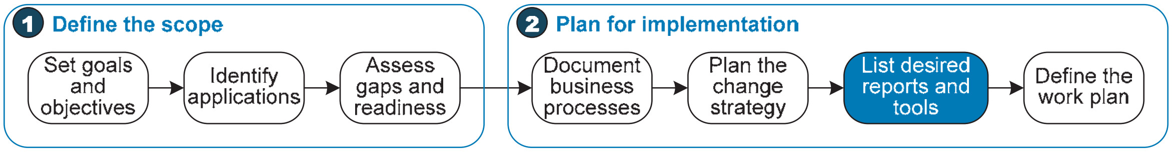


Figure 2-2. Sequence from general goals to specific work plan.

2.3.1 Data Storage

For most agencies at various stages of maturity and for most types of assets, simpler databases and applications are best. For data storage, consider using a desktop database (e.g., Microsoft Access) or a small network database (e.g., Microsoft SQL Server Express). For agencies having a mature data management infrastructure, consider working within that infrastructure to take advantage of the technical support. If the agency has a pavement, bridge, or maintenance management system in place that is working well, consider adding onto that database, rather than starting a new one.

Asset management databases of the kind needed for life expectancy analysis are not large or complex, and many parts may already exist in the agency. For even the most sophisticated applications described in this guide, the basic databases are as follows:

- Geo-referencing database (usually the agency GIS)
- Traffic count database (often included in the GIS)
- Crash database (often maintained outside the transportation agency)
- Asset inventory
- Asset condition (may be a time series of inspections or surveys for each asset)
- Asset vulnerability to natural and man-made hazards (may be a time series)
- Climate condition database (often maintained outside the transportation agency)
- Soil characteristics database (often maintained outside the transportation agency)

For different types of assets, the inventory, condition, and vulnerability assessment databases may be located or maintained at different divisions or units in the agency. For example, there may be separate databases for pavements, bridges, other structures (such as tunnels, culverts, sign structures, signal mast arms, high-mast light poles, and retaining walls), signs, traffic signals, pavement markings, guiderails, curbs and sidewalks, and buildings. Other databases such as those storing climate condition and soil characteristic data can be accessed through federal agency websites.

The NOAA maintains various climate and extreme event data, most of which can be accessed and downloaded at no cost (http://www.ncdc.noaa.gov/oa/mpp/freedata.html). In this report, climate data such as average annual temperature, precipitation, and freeze-thaw cycles were found to be significant for predicting the service lives of culverts and bridges. Average wind speed was also found to be a significant factor in predicting traffic signal life. Most of the data can be downloaded at the climate division level, which groups geographically neighboring counties with similar climates (e.g., Figure 2-3).

Similarly, soil data are maintained by the Natural Resources Conservation Service (NRCS). Soil attributes, such as corrosiveness and frost action potential (ranked from no potential to high potential), significantly affect the asset life of culverts and bridges because of the deterioration of the below-ground components of these structures. The NRCS database contains data on relevant soil attributes and other properties for soils located within each soil survey area (generally the size of a county) by depth (http://soildatamart.nrcs.usda.gov/).

To analyze the significance of climate, soil, and other geographic properties, GIS applications are particularly useful for data storage, with each property having its own layer. For example, Chase et al. (1999) discusses how to add GIS spatial data to National Bridge Inventory (NBI) data.

Certain types of assets could be managed as groups, rather than as individual facilities. For example, all the pavement markings on a segment of road, or even a corridor, could be inventoried and managed as a single unit. This approach works best if all the markings in the group have the same age, same material, same traffic volume, etc., so that they will have uniform life expectancy.

Figure 2-3. United States Climate Divisions *(http://www.cpc.noaa.gov/).*

2.3.2 Foundation Analysis Tools

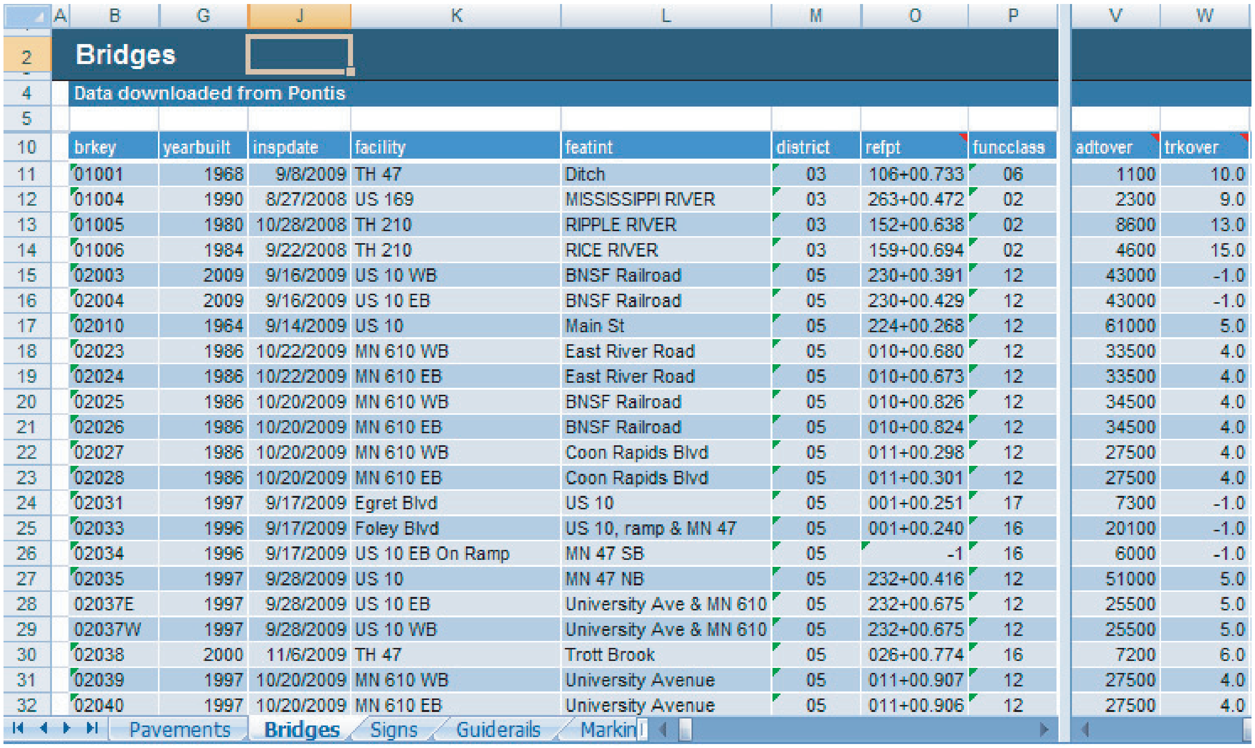
Once the basic data storage tools are established, consider selection of the analysis tools next. For life expectancy analysis, it will often be sufficient to have two sets of tools that make up the foundation of life expectancy analysis:

- A network-level model that computes typical life spans for entire classes of assets using generalized parameters; and
- An asset-level model that computes life expectancy for each asset individually using its age, condition, and other characteristics, often using the network-level model as an input.

Both of these types of tools are addressed in Chapter 4, with example applications in Chapter 5. None of the methods described in this guide are outside the capabilities of a spreadsheet model so these tools should not be considered major software investments (Figure 2-4). The methods and examples described in later chapters frequently refer to spreadsheet functions for statistical calculations. Using spreadsheet software is often the easiest way to implement these models and results in models that are fast, reliable, and inexpensive to develop and maintain.

2.3.3 Applications and Reports

An efficient way to determine the desired applications and reports is to interview each of the potential users of the information identified in the earlier planning steps. The list of potential



Bridges

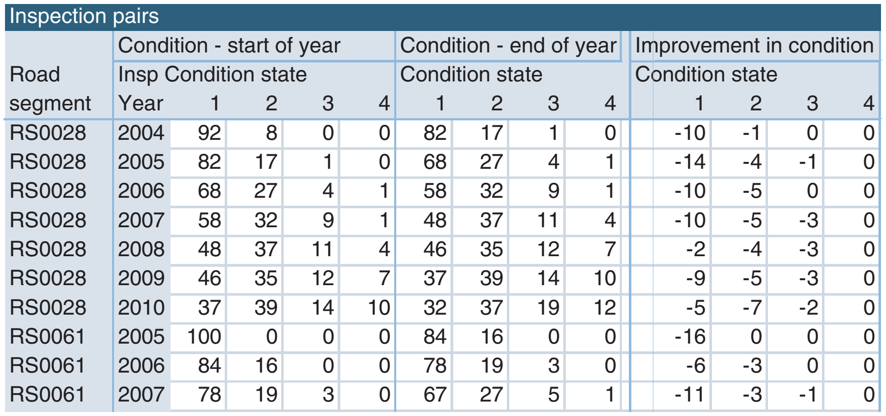
Data downloaded from Pontis

	brkey	yearbuilt	inspdate	facility	featint	district	refpt	funcclass	adtover	trkover
11	01001	1968	9/8/2009	TH 47	Ditch	03	106+00.733	06	1100	10.0
12	01004	1990	8/27/2008	US 169	MISSISSIPPI RIVER	03	263+00.472	02	2300	9.0
13	01005	1980	10/28/2008	TH 210	RIPPLE RIVER	03	152+00.638	02	8600	13.0
14	01006	1984	9/22/2008	TH 210	RICE RIVER	03	159+00.694	02	4600	15.0
15	02003	2009	9/16/2009	US 10 WB	BNSF Railroad	05	230+00.391	12	43000	-1.0
16	02004	2009	9/16/2009	US 10 EB	BNSF Railroad	05	230+00.429	12	43000	-1.0
17	02010	1964	9/14/2009	US 10	Main St	05	224+00.268	12	61000	5.0
18	02023	1986	10/22/2009	MN 610 WB	East River Road	05	010+00.680	12	33500	4.0
19	02024	1986	10/22/2009	MN 610 EB	East River Road	05	010+00.673	12	33500	4.0
20	02025	1986	10/20/2009	MN 610 WB	BNSF Railroad	05	010+00.826	12	34500	4.0
21	02026	1986	10/20/2009	MN 610 EB	BNSF Railroad	05	010+00.824	12	34500	4.0
22	02027	1986	10/20/2009	MN 610 WB	Coon Rapids Blvd	05	011+00.298	12	27500	4.0
23	02028	1986	10/20/2009	MN 610 EB	Coon Rapids Blvd	05	011+00.301	12	27500	4.0
24	02031	1997	9/17/2009	Egret Blvd	US 10	05	001+00.251	17	7300	-1.0
25	02033	1996	9/17/2009	Foley Blvd	US 10, ramp & MN 47	05	001+00.240	16	20100	-1.0
26	02034	1996	9/17/2009	US 10 EB On Ramp	MN 47 SB	05	-1	16	6000	-1.0
27	02035	1997	9/28/2009	US 10	MN 47 NB	05	232+00.416	12	51000	5.0
28	02037E	1997	9/28/2009	US 10 EB	University Ave & MN 610	05	232+00.675	12	25500	5.0
29	02037W	1997	9/28/2009	US 10 WB	University Ave & MN 610	05	232+00.675	12	25500	5.0
30	02038	2000	11/6/2009	TH 47	Trott Brook	05	026+00.774	16	7200	6.0
31	02039	1997	10/20/2009	MN 610 WB	University Avenue	05	011+00.907	12	27500	4.0
32	02040	1997	10/20/2009	MN 610 EB	University Avenue	05	011+00.906	12	27500	4.0

Figure 2-4. Example of organizing the foundation analysis.

applications in Section 1.3, or a similar list tailored to the specific agency, will help to stimulate discussion.

Most of the potential users of the information will prefer to receive periodic reports, on paper or as PDF files. This is the simplest approach for them so they need not remember how to use a spreadsheet or other software tool. Others will require a spreadsheet file (Figure 2-5), a system of related spreadsheet files, or a user interface because they may need to sort or filter the data they are working with or may need to enter or modify data as part of their decision-making responsibility.



Inspection pairs

		Condition - start of year				Condition - end of year				Improvement in condition			
Road	Insp	Condition state				Condition state				Condition state			
segment	Year	1	2	3	4	1	2	3	4	1	2	3	4
RS0028	2004	92	8	0	0	82	17	1	0	-10	-1	0	0
RS0028	2005	82	17	1	0	68	27	4	1	-14	-4	-1	0
RS0028	2006	68	27	4	1	58	32	9	1	-10	-5	0	0
RS0028	2007	58	32	9	1	48	37	11	4	-10	-5	-3	0
RS0028	2008	48	37	11	4	46	35	12	7	-2	-4	-3	0
RS0028	2009	46	35	12	7	37	39	14	10	-9	-5	-3	0
RS0028	2010	37	39	14	10	32	37	19	12	-5	-7	-2	0
RS0061	2005	100	0	0	0	84	16	0	0	-16	0	0	0
RS0061	2006	84	16	0	0	78	19	3	0	-6	-3	0	0
RS0061	2007	78	19	3	0	67	27	5	1	-11	-3	-1	0

Figure 2-5. Example of a spreadsheet-based report.

Some of the design variables to consider when determining the desired reports are as follows:

- Filtering—Some users will want statewide reports, while others will need to see only a subset of the asset inventory (e.g., for a particular district, ownership, or asset type) to match their responsibilities. Certain reports may need to be filtered according to the year or time frame when assets are forecast to reach end-of-life or some other milestone.
- Aggregation—Certain reports should list assets individually, while others will list only groups of assets. In life expectancy analysis, it is especially useful to group assets into cohorts that are geographically close (due to similarities in climate and soils) and reach their end-of-life at about the same time. The life expectancy analysis is very helpful here in grouping facilities into projects.
- Subject matter—Try to tailor reports to each user or user group to fit the exact subject matter they are concerned with. Do not crowd too much information into one report. Ask the users what is relevant, rather than including everything that seems like it might be relevant.
- Sorting—Make sure the order of presentation of items in the report is logical for the end-user's purposes. The best way to ensure the best presentation is to ask the intended users. Often it is useful to sort items in a report according to their urgency for the end-user's attention. Sometimes it is even necessary to make up a priority criterion that is intended for just one user or user group to provide a value on which to sort. For example, if a user wants to emphasize assets that expire soon as well as assets that have particularly high vulnerability to hazards, then it may be necessary to create a criterion that is a combination of these two (or more) data values. Other sorting criteria that are commonly used include asset identifiers, geographic location, current condition, or performance indices.
- Graphics—Most end-users find graphs helpful, and life expectancy analysis provides good opportunities for useful and creative graphics (Figure 2-6). Chapter 5 has examples of relevant types of graphs, all of which can be produced by common spreadsheet and report-writing tools.

2.4 Defining the Work Plan and Resource Needs

Particularly when working with commonly available software, constructing reports is relatively fast and inexpensive, so do not hesitate to plan for a large number of them. During the development phase, plan to interview users for detailed specifications, then produce a prototype report

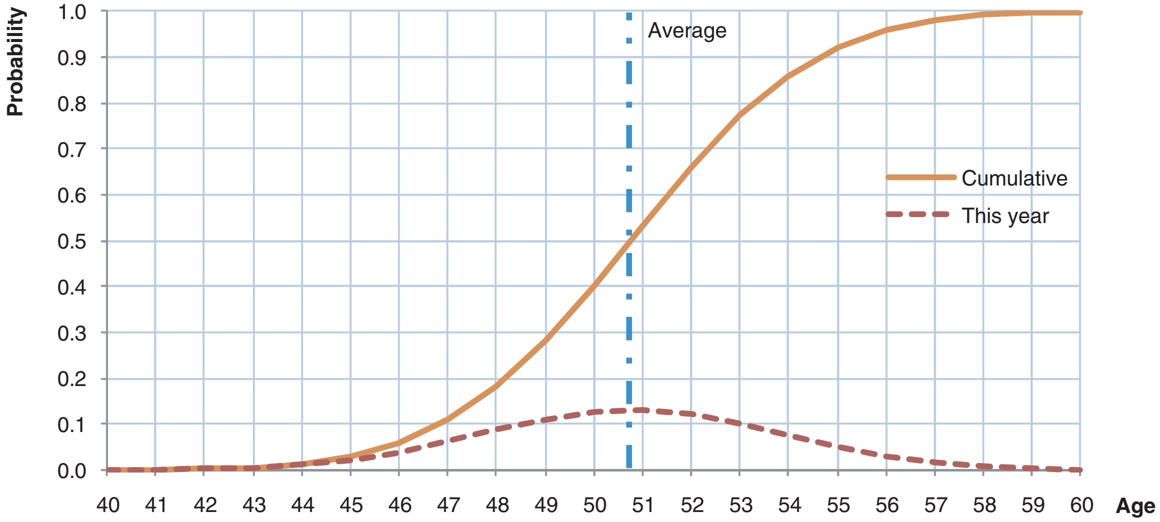


Figure 2-6. Example graphical output, showing uncertainty in life expectancy.

right away (e.g., within a week), ask for feedback, and then modify the report, again within a week. It is important to keep the end-user's attention focused on the report until it is completed and ready to use.

Chapter 1 lays out the main work plan tasks in developing life expectancy applications. An example work plan might be as follows:

- Task 1. Define the scope of the analysis and the needs to be served within the time frame of the project.
- Task 2. Develop an implementation plan.
- Task 3. Define the performance metrics and analysis concepts. Determine data requirements and ascertain how the necessary data are to be obtained. In some cases this may necessitate the launching of new data collection processes, especially for assets other than pavements and bridges, where many agencies have minimal data. Some database development or modification may be needed in this task. Create mockups of tools and reports to be developed in subsequent tasks.
- Task 4. Develop the foundation tools for computing life expectancy for all the asset types within the scope of the project. In many cases, some research or statistical model estimation work may be needed within the scope. Plan to develop a working prototype of each analysis, solicit feedback from users, and then refine the prototype. Document the results in the form of a "User's Manual" or "Technical Memorandum."
- Task 5. Build applications that put the new models to work in real business processes. In some cases, the development work may entail modifications to existing systems, especially pavement, bridge, and maintenance management systems. When a new application is needed, consider using media that facilitate prototyping and rapid development. It is often much easier to attach a separate spreadsheet model or report to a management system database than to try to modify the management system itself.
- Task 6. Ensure that the products of the work have sufficient long-term support. Monitor and evaluate the use of the products and plan for further refinements. Be confident of the results and communicate this confidence to stakeholders.

One of the basic rules of successful change management is to achieve early successes as a means of building and maintaining support. If certain asset types may require an extended work plan duration, perhaps because new data collection is required, then plan to develop other asset types in parallel that have readily available data. Plan a sequence of regularly spaced rollouts to keep interest high while buying time to complete the more difficult parts of the endeavor.

2.5 Setting Quality Metrics and Milestones

The implementation of life expectancy models can be organized and managed just like any other project. The planning phase in Task 2 produces a list of desired tools and applications and the durations and resource requirements for their development, which can be estimated. These can be sequenced on a Gantt chart as in Figure 2-7. After Task 3 is completed, the data requirements and applications will be understood in much more detail so the Gantt chart can be refined.

If delivery is conceptualized as a collection of separate small applications and reports, as recommended in the preceding sections, then progress can be measured by tracking completion of the individual phases of the individual applications. The phases of each application and report are as follows:

- Requirements listing and mockup
- First prototype
- End-user review and comment

- Second prototype
- Subsequent prototypes if applicable
- Final delivery and installation
- Documentation
- Training if applicable

When the work plan consists of small deliverables, it is not necessary to characterize each phase by percent completion because each phase of each deliverable is either complete or not. The total number of completed phases provides the percent completion of the project as a whole. If a delivery does not meet the end-user's quality expectations, then an additional prototype may need to be added, which reduces the percent completion until the additional prototype is delivered.

Following delivery and implementation of the life expectancy models, long-term follow-up is necessary to determine whether the life expectancy predictions are reliable and to make any requested corrections. For long-lived assets such as bridges, it is necessary to break up the life span into condition states or service levels whose duration can be measured in a more reasonable amount of time. The *AASHTO Bridge Element Inspection Manual* (AASHTO 2010) provides an example for this application.

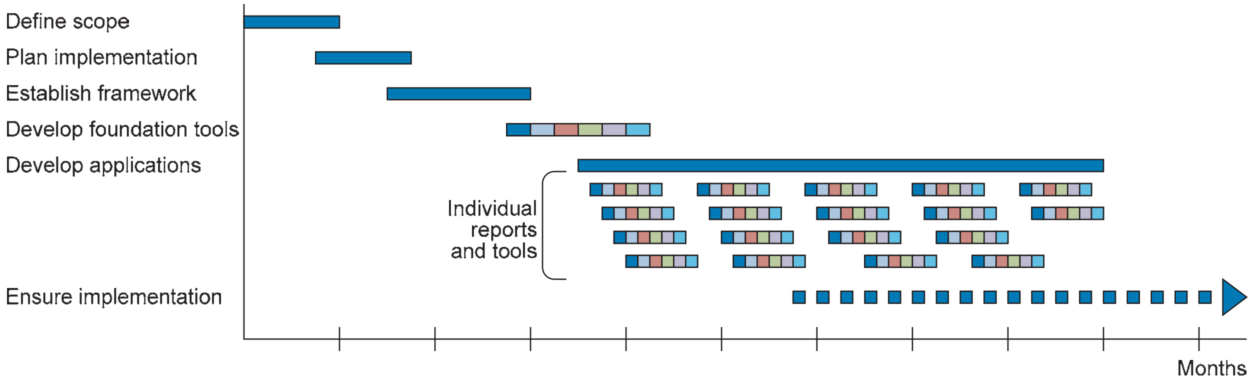


Figure 2-7. Example project schedule for life expectancy tools.

CHAPTER 3

Establish the Framework: How to Design Life Expectancy Models

Life expectancy models can be simple or sophisticated, with various options for policy sensitivity, accuracy, and precision. The selection of models will depend on how the information will be used. For example

- For asset valuation, such as the basic GASB 34 approach, agencies may decide to use straight-line depreciation to convert asset age directly to dollars of value. Total asset lifespan in this case might be determined from a table of accounting conventions, with the remaining life of a given asset determined directly from its age (Figure 3-1, left side).
- For relatively low-value assets whose condition is not routinely monitored (e.g., roadside reflectors), their lifespan might be determined from the manufacturer's recommendations or from agency experience and then applied to a whole population of features. All of the features in the population are replaced at the same time in a single project, even if certain assets in the group were already replaced earlier due to premature failure (Figure 3-1, right side).
- For higher value assets which are custom-made and whose condition is monitored by periodic manual or automated processes (e.g., signs and pavement markings), their condition may be translated directly to life expectancy using simple deterioration models. Replacement is triggered when the condition passes a performance threshold (Figure 3-2, left side). There may be more than one performance measure that could trigger replacement (e.g., pavement cracking and rutting).
- For large constructed facilities, condition and performance may be input to a lifecycle preservation optimization model and/or long-range decision-making process to plan preventive maintenance actions, repairs, rehabilitation, and replacement. Life expectancy is policy-sensitive and may vary based on the maintenance policies and programming decisions made in the intermediate period before the end of the asset's life. The definition of end-of-life may itself be dependent on the agency's policy, program, and project decisions (Figure 3-2, right side).

In order to adopt the more policy-sensitive life expectancy methods, it is not sufficient to perform a more elaborate calculation. In addition, it is necessary for an agency to

- Gather and manage data on asset condition and performance on a regular basis.
- In some cases, gather and manage data on asset repair and replacement activities.
- Develop warrants and feasibility criteria for maintenance, repair, rehabilitation, and replacement.
- Develop data on crew and/or contractor capabilities, as well as materials and equipment, to support life-extension activities.
- Develop planning processes that can forecast and program life-extension activities at the most favorable time.
- Earn stakeholder confidence that the life-extension activities are cost-effective enough so that an appropriate budget level is established for them.

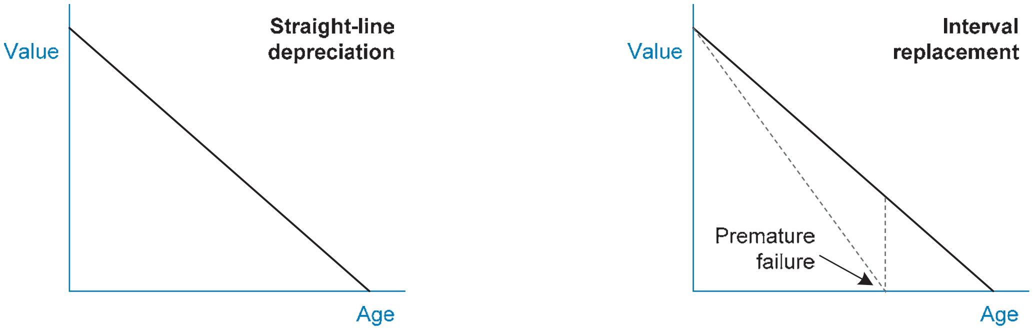


Figure 3-1. Pre-determined interval-based life expectancy.

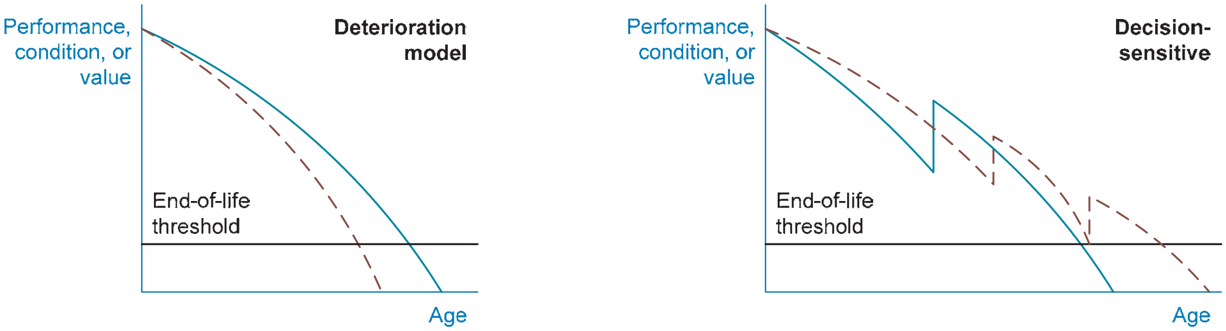


Figure 3-2. Condition or performance-based life expectancy.

This is why the concept of agency maturity, introduced in Chapter 1, is so important for selecting appropriate methods for calculating life expectancy. Agencies that are higher on the asset management maturity scale tend to conduct condition and performance monitoring on a wider range of facilities and tend to have end-of-life definitions that are more often policy-sensitive. This is just another way of saying that they are proactive in their decision-making and have more alternatives available for extending asset life instead of automatic replacement.

3.1 Defining Performance Measures

One of the reasons for implementing life expectancy analysis is to use it as an outcome measure of infrastructure health or of preservation work accomplished. Often an informal justification given for preservation activity is "to extend asset life." Whether this argument is understandable or verifiable may depend on context. Consider, for example, the following scenarios:

1. The asset is at the end of its normal life expectancy. It is in poor condition or performing at a level that is below agency standards. Replacement is a justifiable alternative. There is also a repair or rehabilitation alternative that is less expensive than replacement and that will alleviate the current deficiencies for a period of time before replacement once again must be considered.
2. The asset is at the end of its life expectancy. It is in serviceable condition and functions according to agency standards. There is some risk that the asset might fail suddenly and cause an interruption to traffic.
3. The asset was procured with a 10-year life expectancy but is already performing below standard after 5 years. It can be repaired or rehabilitated, which may correct the deficiency and provide 2 to 3 years of additional life. Subsequent repair may or may not be able to offer further life extension.

4. The asset consists of separate and distinct components, and each component has its associated set of preservation actions that may and may not influence the life of other components. For example, consider a bridge having 25 years of remaining life that is functioning well, but the protective steel coating is deteriorating. If allowed to remain as it is, the steel elements of the bridge might last only 10 years. If the coating is replaced, the bridge is likely to realize its full 25 remaining years. The non-steel elements of the bridge, such as concrete piers and abutments, might have 25 years of life remaining, or more, even if no maintenance is performed.

Scenario 1 is the easiest to understand and measure. If an asset is not performing up to standard, for example, a guiderail that cannot withstand a required impact force or a sign whose retroreflectivity is below standard, then the potential justification for immediate replacement is understood. If an alternative is available that is less expensive than replacement, but offers fewer years of life than replacement, then its justification might be made based on funding availability or lifecycle cost analysis (Figure 3-3).

Scenario 2 is more difficult to measure, because it expresses a risk of failure rather than observed failure. The asset might remain in satisfactory service for many years or it might fail the next day (Figure 3-4). With sufficient historical data from the manufacturer or from the agency's internal records, the probability of failure might be quantified as a function of age and any potential preventive maintenance actions could be identified. The optimal replacement time then can be determined from a probabilistic analysis of its lifecycle cost.

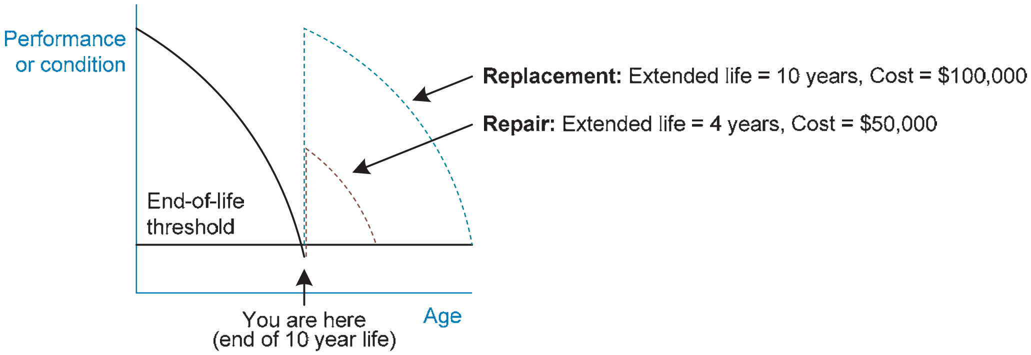


Figure 3-3. Extended life expectancy as a measure of project benefit.

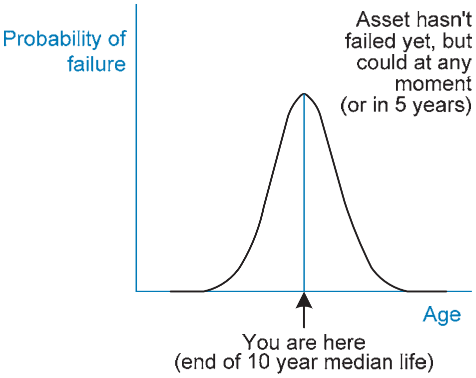


Figure 3-4. Failure at an uncertain time.

Situations such as Scenario 2 are considered for assets where sudden failure would be catastrophic (e.g., a high-mast light pole might fracture and fall onto vehicles in traffic) or where mobilization costs to respond to isolated failures are high, relative to the cost of a replacement asset or component (e.g., traffic signal lamps or pavement markings).

For Scenarios 1 and 2, the fact that an asset has already reached its life expectancy, makes it easier to use life expectancy as a performance measure for certain audiences and purposes. Compared to lifecycle cost, life expectancy may be easier for laypeople to understand. For elected officials, the ability to postpone expenditures to a point in time longer than the election cycle may appear to be a very tangible and relevant decision criterion.

Scenario 3 is also more difficult to measure. In this case it is necessary to estimate remaining life for the asset under one or more scenarios of repair as well as a replacement asset. Each of these measurements has uncertainty. It is possible to use remaining life as a performance measure to justify investments; but, given that there are multiple estimates of remaining life, depending on current or future actions, and given that all such estimates are difficult to verify, the credibility and comprehensibility of asset life estimates may be jeopardized. In such cases, lifecycle cost becomes a more manageable performance measure to use instead of life expectancy.

Scenario 4 presents even more complications that make it difficult to use life expectancy as a performance measure. In this case, there is a possibility of replacement of just a portion of an asset and other preventive maintenance or corrective actions may exist. Even in a do-nothing scenario, life expectancy is uncertain in Scenario 4. Future deterioration and future agency decisions have many sources of uncertainty, such as weather, traffic, and future budgets (Figure 3-5).

In Scenarios 3 and 4, it is always useful to quantify life expectancy because this measure sets a time window within which any repair or rehabilitation actions may be considered and in which any benefits of such actions must be realized. However, life expectancy in this case is not used as a performance measure to quantify the benefits of the work. Instead, it is an intermediate result in an analysis where lifecycle cost and other more direct measures of performance (e.g., safety, resilience, travel speed, reliability, and comfort) are to be optimized.

In contrast, for assets that have short or very predictable lifespans, life expectancy can be used not only as a measure of benefit, but even as a measure of current economic condition. If the average age of traffic signal controllers in a highway agency is 13 years, and the life expectancy for those assets is 15 years (i.e., 2 additional years), then this describes a relatively adverse economic situation where higher than normal replacement needs can be expected in the near future, compared to an inventory that is only, say, 5 years old.

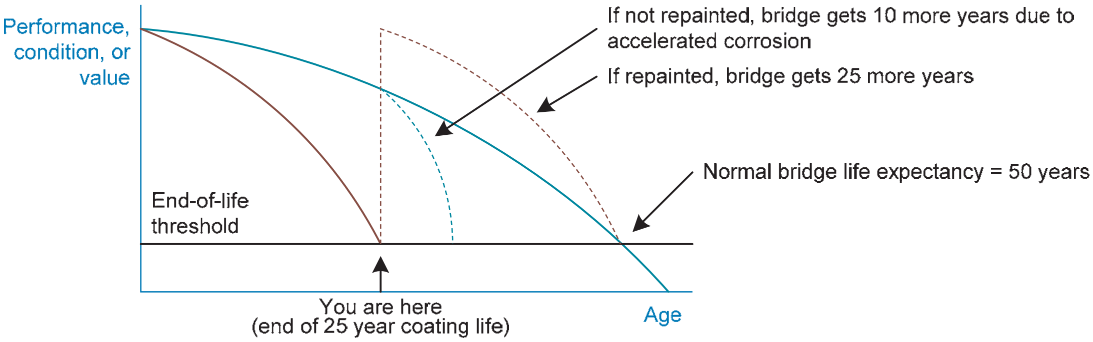


Figure 3-5. Portions of an asset with shorter life expectancy.

3.2 Conceptualizing the Analysis

The preceding sections described a top-down process that leads to the design of a life expectancy framework. The process starts with an understanding of the agency personnel and stakeholders who need the information and how they will use such information. The process continues with a concept for applications that produce the needed information and reports. This vision is refined using knowledge of the types of assets to be considered and their typical lifespans and typical agency actions.

3.2.1 Defining End-of-Life

Life expectancy is the time between a given point in an asset's life and a later time when the asset must be removed or replaced. Usually the starting point is the manufacturing date, the date when the asset is placed into service, the present date from which remaining life is measured, or the date of some future action or decision. The starting point can usually be determined with some certainty based on the purpose of the analysis. Determination of the ending point, however, often must be carried out with due circumspection. Here are some of the possibilities:

- For an asset designed to fail suddenly, the date of failure. This definition would apply to such assets as lamps and motors (Figure 3-6, left side).
- For an asset designed to become obsolete at a definite or identifiable time, the date when the obsolescence event takes place. This might apply to equipment whose support is discontinued as of a specified date or guiderails that will become obsolete when a new, stricter standard is adopted (Figure 3-6, right side). This is often referred to as the functional life of the asset.
- For assets where obsolescence is directly defined by age, the time when the predefined lifespan runs out. For example, certain customer amenities in highway rest areas might be deemed to be out of style or "worn out" if their age exceeds 6 years (Figure 3-7, left side).
- Certain assets whose life might be defined by condition may have their end-of-life defined by age or accumulated utilization instead if their condition is not routinely measured. For example, highway signs might be replaced at a given age, rather than by tracking retro-reflectivity and damage (Figure 3-7, left side).
- For assets whose life is defined by utilization, life expectancy is the time when the utilization threshold is reached. This might apply to consumable materials and can apply to structural parts that are subject to metal fatigue (Figure 3-7, right side).
- When an asset has a definite failure state but its failure would be catastrophic or the cost of responding to isolated failures would be high, end-of-life might be determined from a probability distribution of lifespan data combined with a lifecycle cost model. When the cost of unexpected failure is high, the optimal replacement interval may be less than the median time to fail (Figure 3-8, left side). Fatigue life is an example.
- When an asset does not have a definite failure state or where a condition of failure entails unacceptable safety or risk levels, end-of-life may be determined by defining terminal criteria for condition or other performance characteristics. This approach is typical of pavements and bridges (Figure 3-8, right side) and is often called structural life.
- If portions of an asset can be replaced without replacing the entire asset, then it becomes relevant to define end-of-life in terms of the replaceable parts. This is especially true of constructed facilities and of vehicles (Figure 3-9).
- When an agency has methods of correcting end-of-life conditions or preventing them through maintenance activity, end-of-life depends on a calculation of the optimal application of such methods. Given that the lives of transportation assets cannot be extended forever, the end-of-life may be determined by physical characteristics, obsolescence, extreme events, or project interrelationships that limit further use of corrective or preventive measures. For example, a bridge might be repaired and rehabilitated regularly until finally material degradation and traffic demand necessitate replacement by constructing a larger and/or stronger structure (Figure 3-10).

- In the most general case where an asset has multiple performance measures, where the agency has corrective and preventive alternatives for preservation, and where uncertainty is modeled probabilistically, simulation methods might find the optimal life expectancy.

It is often the case that the end of an asset's life can be defined by more than one of the criteria described above. This is also the case at the network level when more than one of these criteria may combine to determine future replacement expenditure levels.

The performance of highway assets relates to (1) operating characteristics, such as level of service (LOS), levels of safety, mobility, or congestion or (2) physical conditions, such as pavement serviceability rating (PSR), bridge health index, and road sign retroreflectivity. Interventions (e.g., repair, maintenance, rehabilitation, and reconstruction to highway assets) using warrants based on time intervals are easy to implement but may result in unintended delayed or

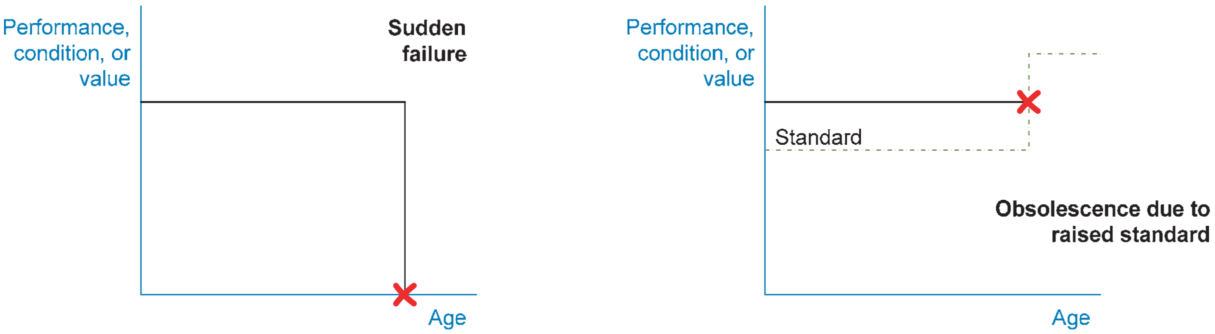


Figure 3-6. End-of-life criteria.

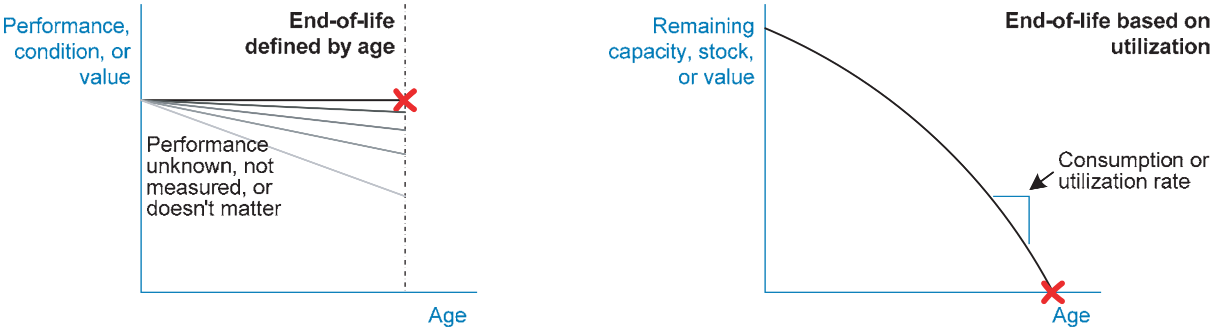


Figure 3-7. Additional end-of-life criteria.

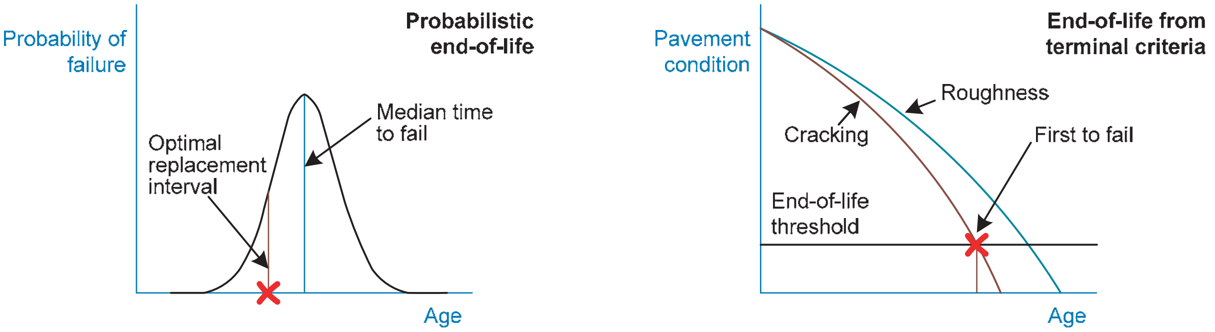


Figure 3-8. Additional end-of-life criteria.

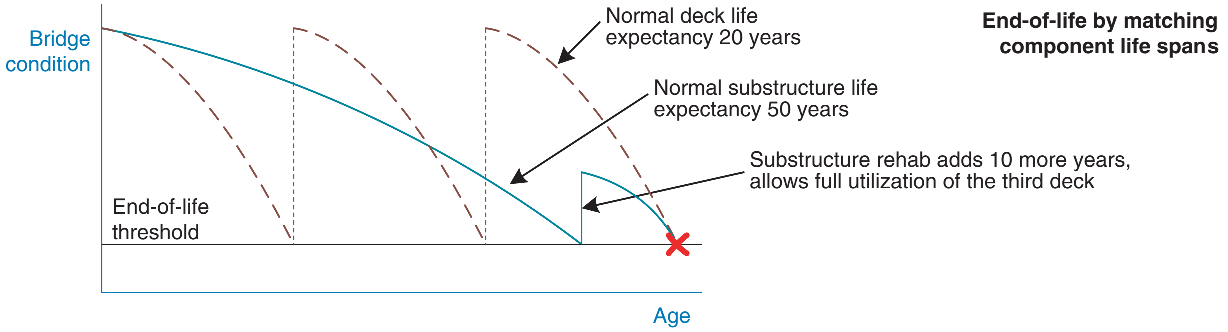


Figure 3-9. Planning end-of-life by coordinating the lifespans of components.

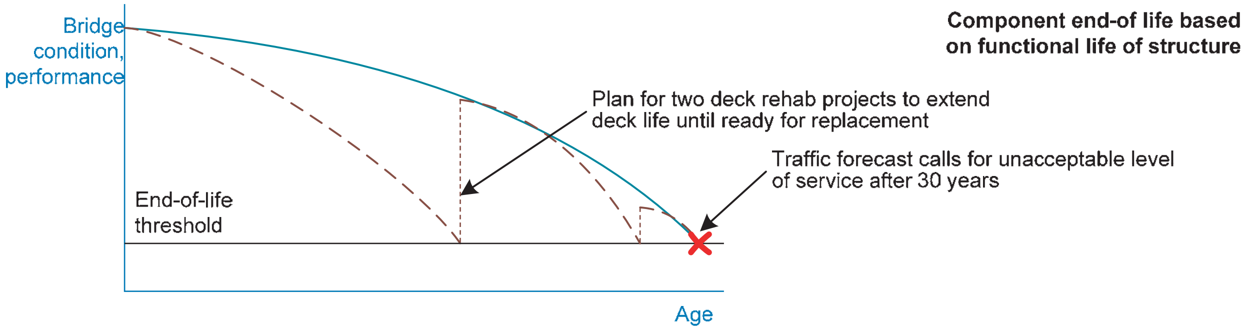


Figure 3-10. Planning component life based on functional life.

accelerated action. A performance-based warrant presents a superior alternative. Such a threshold can be set by one of the following ways:

- Expert opinion
- Historical records
- Optimization

Road agencies may combine more than one of these approaches. Bilal et al. (2011) proposed a general optimization framework to determine the optimal threshold for highway assets where maximum possible benefits of an intervention are achieved at the minimum possible cost. He determined that the optimal thresholds were sensitive to changes in user cost weight relative to agency cost and the user cost components used. Pavement and bridge management systems can often be used to establish these thresholds through lifecycle cost optimization.

A common thread in these definitions is that, in most cases, end-of-life is certain only in the past. When evaluating an asset in service, its end-of-life depends on a decision about the optimal time to replace the asset, given anticipated deterioration and available life-extension actions. This determination is often referred to as economic life. As agencies become more mature in their asset management practices, they become more adept and sophisticated at finding the optimal life expectancy and in deploying life-extension methods.

To evaluate the effectiveness of maintenance strategies, the following techniques are recommended:

- Segment data. Calibrate models for each level of maintenance activity.
- Incorporate as an independent variable. Evaluate the effect of maintenance through parameters found in model calibration.
- Add life extension on top of model prediction. Predict life based on a consistent level of maintenance or without maintenance; then add/subtract life extensions if known. For Markov chains, an improvement in condition state can be used to extrapolate a new life prediction.

Comparisons of maintenance strategies can then be made on a lifecycle basis using the life expectancy estimate as the analysis period. With increasing use of automation and information technology, road agency databases on maintenance activities are becoming more enriched, enabling the inclusion of maintenance history in the explanatory variables to better model highway asset performances.

3.2.2 Intervention Possibilities

Many types of transportation assets are candidates, at certain points in their lives, for possible intervention actions that may extend their lives. The economic attractiveness of these actions may depend on their cost and effectiveness. The cost may depend on economies of scale, traffic volume (and traffic control measures), availability of equipment and labor, and contractual relationships. Effectiveness may depend on the availability of the materials used in the asset, the current condition of the asset, the weather, and the capabilities of the crew.

When an agency has various intervention possibilities at its disposal, it is in a better position to optimize the lifecycle preservation actions for each asset. It is especially helpful to have alternatives that provide different increments of life extension at different costs. For example

- Routine maintenance activities that prevent the onset of physical deterioration, such as washing and sealing;
- Repair and corrective actions that restore damaged protective systems or prevent acceleration of damage, such as painting and patching; and
- Rehabilitation actions that replace deteriorated material or components to restore full functionality or stop damage progression.

Timing plays a significant role in the attractiveness of an intervention for a given situation. For example, for urban highway sidewalk slabs, an agency might find that leveling of the slabs is too expensive to perform routinely as an alternative to replacement. But for a road that is to be widened in 5 years, leveling might be just enough to restore the facility to agency standards as a stop-gap measure.

3.2.3 Modeling Performance and Uncertainty

Estimates of life expectancy depend on quantitative models of asset deterioration in terms of condition or performance. “Performance” in this case refers to the ability of an asset or group of assets to satisfy customer or stakeholder expectations. In order to select the right type of model for a given asset type and application, the distinction between continuous measures and discrete measures needs to be made:

- A continuous performance measure is one that changes on a smooth scale, which can be broken into meaningful increments of any size. Examples include the International Roughness Index (IRI), sign retroreflectivity, and traffic volume/capacity ratio. The NBI condition ratings do not fall in this category because the interval between two rating levels cannot be meaningfully broken into smaller intervals; for example, there is no meaning for a rating of 8.5.
- A discrete performance measure is one that changes on a step-wise scale, each level having a definition that may be independent of other levels. For example, a lamp is either functional or non-functional; sidewalk sections might be rated in terms of levels of service (e.g., a section at level A may have no tripping hazards of more than 1 inch in height); or bridge elements might be described in terms of condition states (e.g., a steel girder in condition state 2 may have paint that is peeling or chalking without exposure of metal).

Figure 3-11 contrasts these types of measures. The mathematical differences between them are important for quantifying these models accurately with historical data.

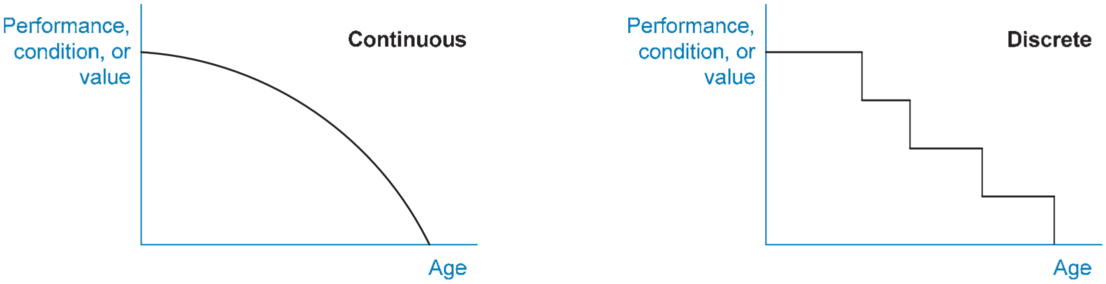


Figure 3-11. How performance changes over time.

When trying to forecast future condition or performance, another important distinction is between deterministic and probabilistic models. Figure 3-11 shows deterministic models, where the performance at any given point in time is assumed to be known with certainty. Figure 3-12 shows these model types when using probabilistic models.

In a probabilistic model, at any given time, it is possible to predict more than one performance level. A continuous model, such as the left side of Figure 3-12, generally describes future performance using a mathematical function for the most likely value and another function to describe the uncertainty surrounding this value. A discrete probabilistic model, such as the right side of Figure 3-12, generally describes each condition state or service level as a probability of that level at each point in time.

To keep the math simple, uncertainty in probabilistic continuous models is often quantified using a constant standard deviation or a standard deviation that increases with time. For discrete models, uncertainty is often quantified using a constant transition probability from one state to another state in one year. This type of model is called a Markov model.

A common variation on the discrete probabilistic model is the case where there are only two possible states (e.g., operational versus failed), and the probability of each state varies with age. Figure 3-13 shows an example. This model is called a survival probability model. Chapter 4 will show that this type of model is especially useful for the simplest and most common types of life expectancy analyses. If a more sophisticated picture of probabilistic deterioration to non-failed states is required, as when analyzing life-extension possibilities or maintenance strategies, then a multinomial choice model such as an ordered probit model may be useful.

In program planning analysis, uncertainty is very important. Figure 3-13 shows an analysis involving a population of signs. Based on median life expectancy for a cohort of signs, it appears that no funding for replacement will be needed during the 10-year program. However, when

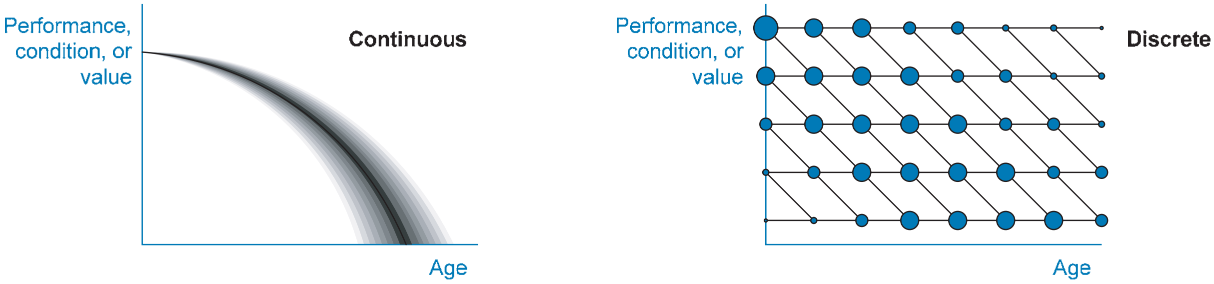


Figure 3-12. Probabilistic models of performance.

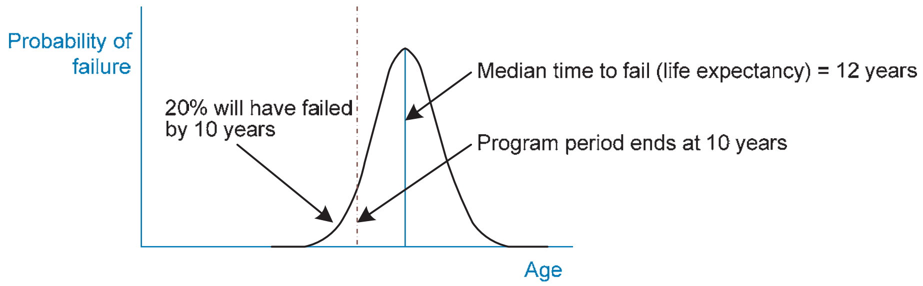


Figure 3-13. Role of uncertainty in program planning.

uncertainty is quantified, it is found that 20% of the cohort will have failed by the end of that 10-year period. This result implies that funding will, in fact, be needed.

3.3 Determining Data Requirements

From the analysis of the stakeholders and their information needs, it becomes possible to list the specific types of assets for which it would be useful to have life expectancy information. Then the agency can determine how the condition and performance of each asset type should be measured to enable performance management, definition of the end-of-life, selection of interventions, and modeling of deterioration.

For certain asset types, particularly bridges and pavements, the agency is likely to have data collection processes in place. In most cases, the existing data will be sufficient for life expectancy analysis. For other assets, where data are not already available, the agency should investigate whether the gathering of additional data is worth the expense.

Given that the value of life expectancy analysis comes from the ability to make better decisions, one way to approach the estimation of the value of data collection, is to try to estimate the cost savings associated with improved decision-making, made possible by additional data.

As the previous sections showed, an accurate estimate of remaining life can help an agency to optimize life-extension activities, to find the right level of investment to minimize the lifecycle cost of each asset. Chapter 5 presents quantitative methods to apply life expectancy information in lifecycle cost analysis. By providing judgment-based estimates of model inputs, the analyst can prepare a pro forma lifecycle cost analysis using current decision-making methods and compare them with optimized methods using better data. To the greatest extent possible, the same level-of-service standards and end-of-life definitions should be used for both analyses. The difference in lifecycle costs would then be an estimate of the savings attributable to improved data.

To maximize cost savings, the agency should consider several strategies to minimize the cost of data collection:

- Limit data collection to a representative, yet random sample of the asset type to be analyzed (Hensing and Rowshan 2005). If it is acceptable for some facilities to "fall through the cracks" and go unmeasured, then a sampling approach can vastly reduce the cost of data collection (Figure 3-14).
- Use deterioration models to monitor intermittently the current condition or performance. A common practice among utility companies is to read the electric meter once every 2 or

3 months and estimate usage for the intervening months. A similar approach can be used for asset data collection to reduce costs.

- Develop models of replacement interval as a function of asset characteristics. In the best case scenario, this might enable a complete avoidance of routine condition surveys for certain types of assets. This is especially useful for cases where asset data collection is relatively expensive in comparison to replacement cost.
- Increase the data collection interval for assets that are new or for other asset characteristics that are correlated with smaller changes in performance over time. For example, most bridges are inspected on a 2-year interval, but certain types of new structures can qualify for longer intervals—up to 4 years.
- Consider the use of automated data collection methods whenever possible. Automated pavement surveys using vehicles that can collect useful data on roadside assets as well are very common (Figure 3-15).
- Share data collection costs with other agencies to build economies of scale. State DOTs often perform data collection activities for local agencies to keep statewide costs as low as possible.

Appropriate use of these data collection strategies can facilitate a meaningful life expectancy analysis, even for relatively minor asset types.

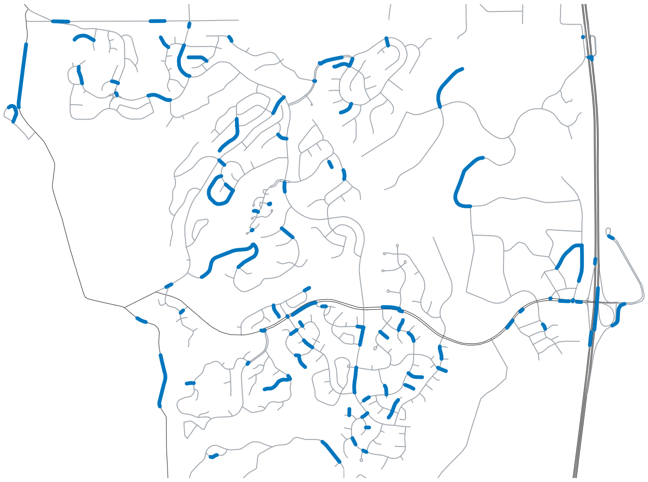


Figure 3-14. Example of 10% section sampling.

***Figure 3-15. Example of automated data collection equipment** (Hensing and Rowshan 2005).*

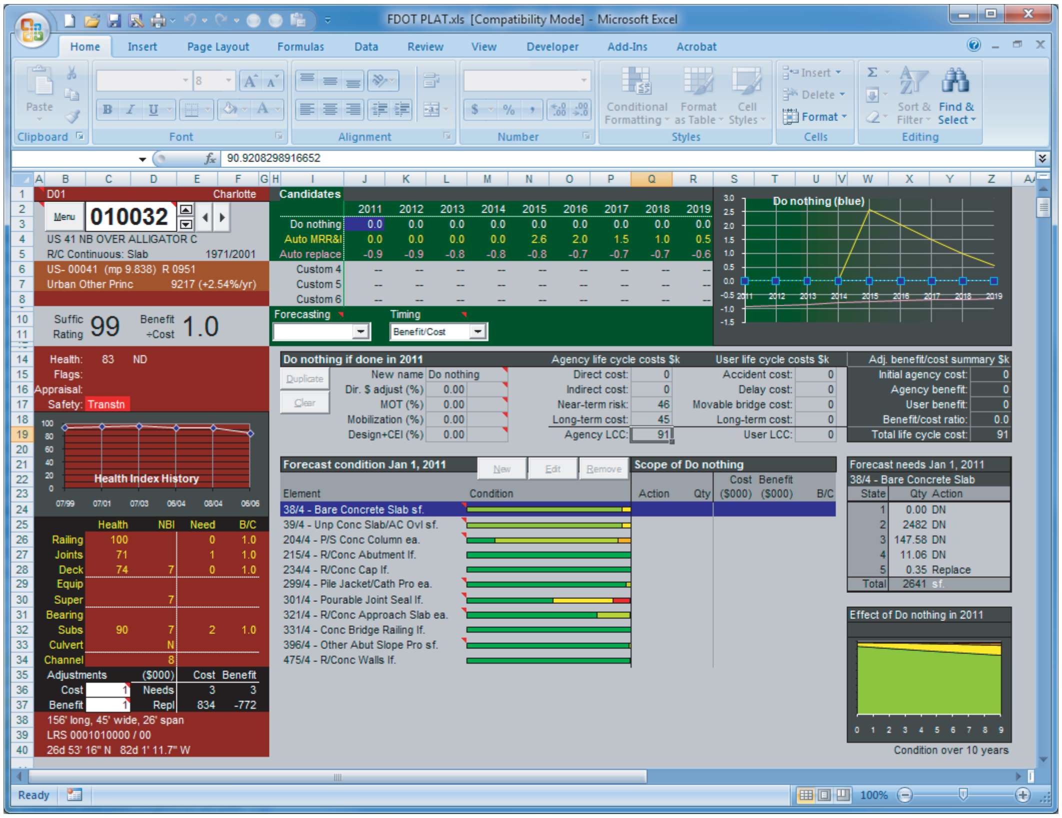
3.4 Mocking Up Tools and Reports

For efficient development of asset management applications, it helps to begin with a set of mockups. Spreadsheet software is an effective tool for rapid development and refinement of mockups of new software tools. Mockups can be converted to working prototypes by adding formulas to implement analysis equations, such as the calculation of life expectancy or lifecycle cost.

Once end-users are satisfied with the mockups, the spreadsheet files can be used as models for the full software application. Figures 3-16 through 3-19 are examples. In each case the mockup evolved into a prototype, and then into the final application. The figures and examples included throughout this guide and in the software available on the TRB website can form the basis for many useful mockups for life expectancy analysis.

3.5 Gaining Buy-in and Building Demand

An important reason for developing compelling mockups is the ability to use them to stimulate (1) agency interest in the study product and (2) demand for better information. Outside stakeholders, and even senior managers who are not technically inclined, might not realize the kinds of information that the agency would be empowered to produce using the study product. Even if stakeholders lack the interest or preparation to appreciate the analysis itself, they might find it easy to visualize how they would use a life expectancy report once they see one.



90.9208298916652

D01 Charlotte

010032

US 41 NB OVER ALLIGATOR C

R/C Continuous: Slab 1971/2001

US- 00041 (mp 9.838) R 0951

Urban Other Princ 9217 (+2.54%/yr)

Suffic Rating 99 Benefit ÷Cost 1.0

Health: 83 ND

Flags:

Appraisal:

Safety: Transtn

Candidates	2011	2012	2013	2014	2015	2016	2017	2018	2019
Do nothing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Auto MRR&I	0.0	0.0	0.0	0.0	2.6	2.0	1.5	1.0	0.5
Auto replace	-0.9	-0.9	-0.8	-0.8	-0.8	-0.7	-0.7	-0.7	-0.6
Custom 4	--	--	--	--	--	--	--	--	--
Custom 5	--	--	--	--	--	--	--	--	--
Custom 6	--	--	--	--	--	--	--	--	--

Forecasting:

Timing: Benefit/Cost

	Health	NBI	Need	B/C
Railing	100		0	1.0
Joints	71		1	1.0
Deck	74	7	0	1.0
Equip				
Super		7		
Bearing				
Subs	90	7	2	1.0
Culvert		N		
Channel		8		

Adjustments		($000)	Cost	Benefit
Cost	1	Needs	3	3
Benefit	1	Repl	834	-772

156' long, 45' wide, 26' span

LRS 0001010000 / 00

26d 53' 16" N 82d 1' 11.7" W

Do nothing if done in 2011

New name: Do nothing

Dir. $ adjust (%): 0.00

MOT (%): 0.00

Mobilization (%): 0.00

Design+CEI (%): 0.00

Agency life cycle costs $k	
Direct cost:	0
Indirect cost:	0
Near-term risk:	46
Long-term cost:	45
Agency LCC:	91

User life cycle costs $k	
Accident cost:	0
Delay cost:	0
Movable bridge cost:	0
Long-term cost:	0
User LCC:	0

Adj. benefit/cost summary $k	
Initial agency cost:	0
Agency benefit:	0
User benefit:	0
Benefit/cost ratio:	0.0
Total life cycle cost:	91

Forecast condition Jan 1, 2011

Element	Condition
38/4 - Bare Concrete Slab sf.	
39/4 - Unp Conc Slab/AC Ovl sf.	
204/4 - P/S Conc Column ea.	
215/4 - R/Conc Abutment lf.	
234/4 - R/Conc Cap lf.	
299/4 - Pile Jacket/Cath Pro ea.	
301/4 - Pourable Joint Seal lf.	
321/4 - R/Conc Approach Slab ea.	
331/4 - Conc Bridge Railing lf.	
396/4 - Other Abut Slope Pro sf.	
475/4 - R/Conc Walls lf.	

Scope of Do nothing

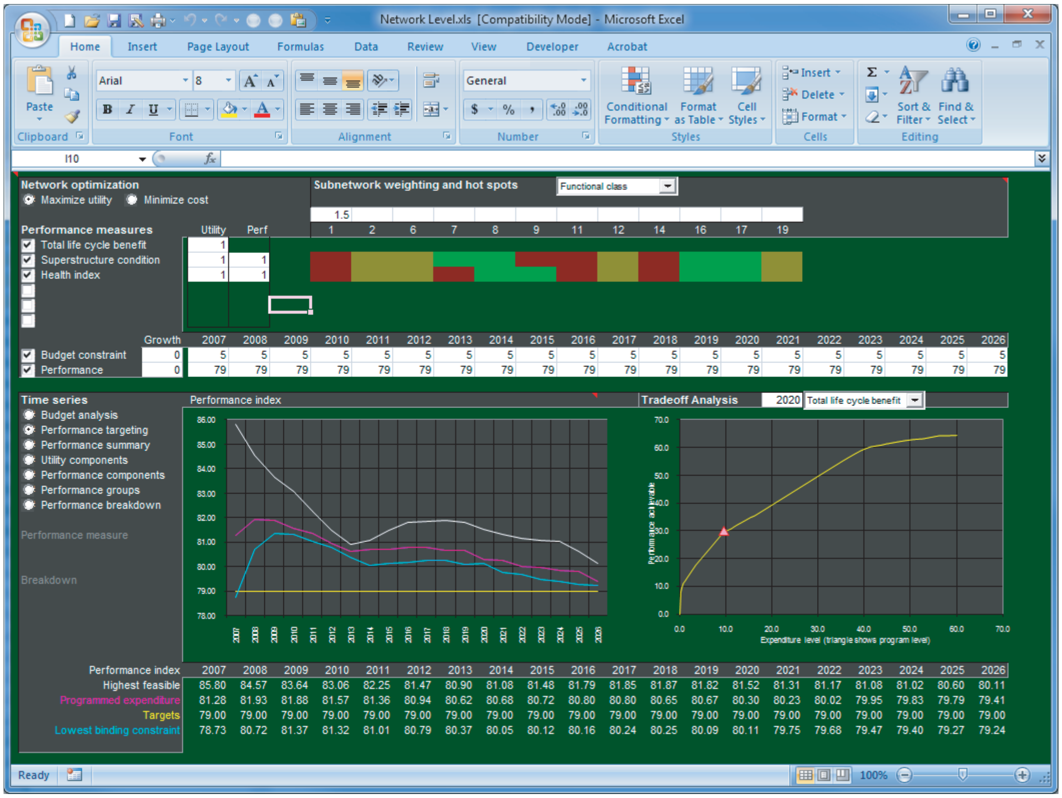
Action	Qty	Cost ($000)	Benefit ($000)	B/C

Forecast needs Jan 1, 2011

38/4 - Bare Concrete Slab

State	Qty	Action
1	0.00	DN
2	2482	DN
3	147.58	DN
4	11.06	DN
5	0.35	Replace
Total	2641	sf.

Figure 3-16. Lifecycle cost analysis application used in Florida DOT.



Network optimization

● Maximize utility ○ Minimize cost

Subnetwork weighting and hot spots

1.5											
1	2	6	7	8	9	11	12	14	16	17	19

Performance measures

	Utility	Perf
☑ Total life cycle benefit	1	
☑ Superstructure condition	1	1
☑ Health index	1	1
☐		
☐		
☐		

	Growth	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
☑ Budget constraint	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
☑ Performance	0	79	79	79	79	79	79	79	79	79	79	79	79	79	79	79	79	79	79	79	79

Time series

○ Budget analysis
● Performance targeting
○ Performance summary
○ Utility components
○ Performance components
○ Performance groups
○ Performance breakdown

Performance measure

Breakdown

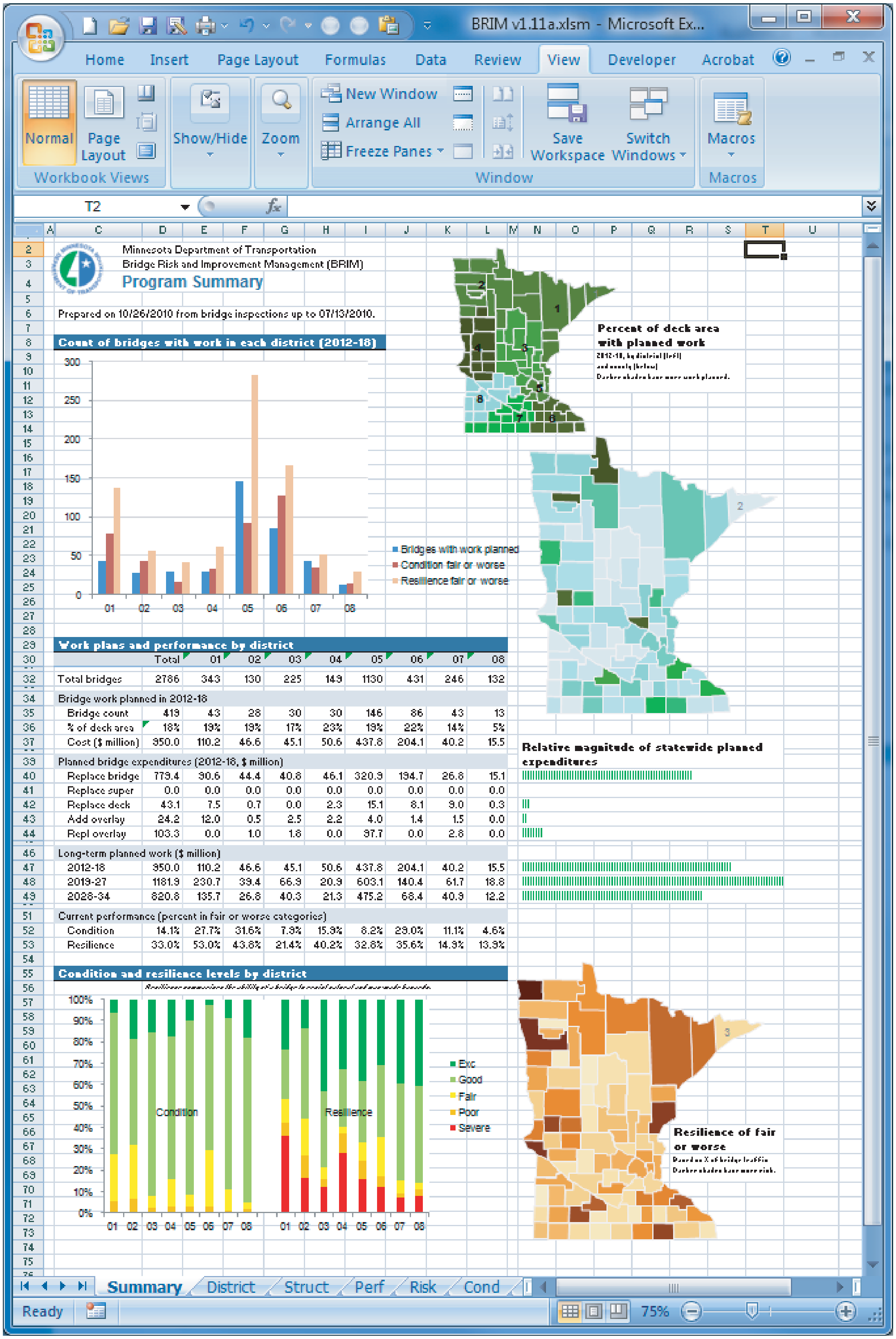
Performance index

Tradeoff Analysis 2020

Performance index	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Highest feasible	85.80	84.57	83.64	83.06	82.25	81.47	80.90	81.08	81.48	81.79	81.85	81.87	81.82	81.52	81.31	81.17	81.08	81.02	80.60	80.11
Programmed expenditure	81.28	81.93	81.88	81.57	81.36	80.94	80.62	80.68	80.72	80.80	80.80	80.65	80.67	80.30	80.23	80.02	79.95	79.83	79.79	79.41
Targets	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00
Lowest binding constraint	78.73	80.72	81.37	81.32	81.01	80.79	80.37	80.05	80.12	80.16	80.24	80.25	80.09	80.11	79.75	79.68	79.47	79.40	79.27	79.24

Figure 3-17. Resource allocation tool published in NCHRP Report 590.

Often a successful implementation tactic for asset management tools is to prototype a small set of reports using a very simple version of the analysis, working around the data gaps that may exist. The product may be very rough at first and should be carefully labeled as such. Once managers and stakeholders develop a vision for better asset management, they are more likely to support the data collection and development work necessary to make the vision a reality.



Minnesota Department of Transportation
Bridge Risk and Improvement Management (BRIM)
Program Summary

Prepared on 10/26/2010 from bridge inspections up to 07/13/2010.

Count of bridges with work in each district (2012-18)

Percent of deck area with planned work
2012-18, by district (left)
and county (below)
Darker shades have more work planned.

Work plans and performance by district

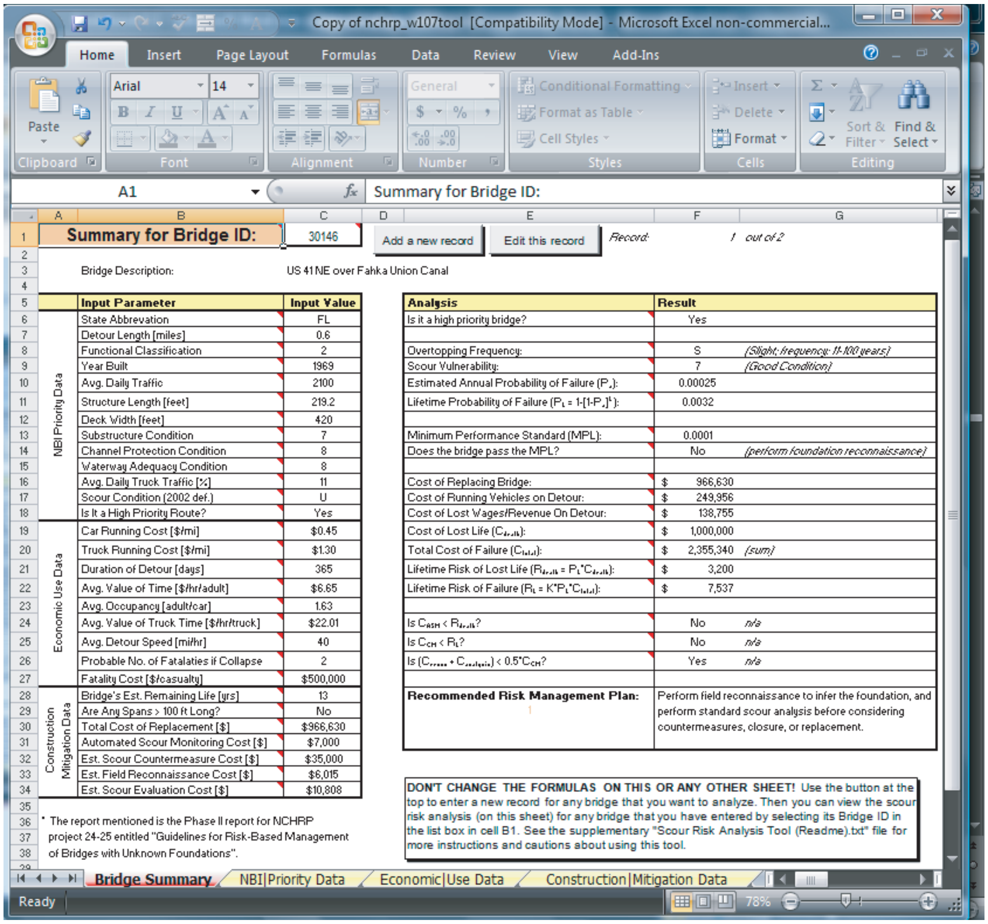
	Total	01	02	03	04	05	06	07	08
Total bridges	2786	343	130	225	149	1130	431	246	132
Bridge work planned in 2012-18									
Bridge count	419	43	28	30	30	146	86	43	13
% of deck area	18%	19%	19%	17%	23%	19%	22%	14%	5%
Cost ($ million)	950.0	110.2	46.6	45.1	50.6	437.8	204.1	40.2	15.5
Planned bridge expenditures (2012-18, $ million)									
Replace bridge	779.4	90.6	44.4	40.8	46.1	320.9	194.7	26.8	15.1
Replace super	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Replace deck	43.1	7.5	0.7	0.0	2.3	15.1	8.1	9.0	0.3
Add overlay	24.2	12.0	0.5	2.5	2.2	4.0	1.4	1.5	0.0
Repl overlay	103.3	0.0	1.0	1.8	0.0	97.7	0.0	2.8	0.0
Long-term planned work ($ million)									
2012-18	950.0	110.2	46.6	45.1	50.6	437.8	204.1	40.2	15.5
2019-27	1181.9	230.7	39.4	66.9	20.9	603.1	140.4	61.7	18.8
2028-34	820.8	135.7	26.8	40.3	21.3	475.2	68.4	40.9	12.2
Current performance (percent in fair or worse categories)									
Condition	14.1%	27.7%	31.6%	7.9%	15.9%	8.2%	29.0%	11.1%	4.6%
Resilience	33.0%	53.0%	43.8%	21.4%	40.2%	32.8%	35.6%	14.9%	13.9%

Relative magnitude of statewide planned expenditures

Condition and resilience levels by district

Resilience of fair or worse
Based on % of bridge traffic
Darker shades have more risk.

Figure 3-18. Risk analysis report developed for Minnesota DOT.



Summary for Bridge ID: 30146

Record: 1 out of 2

Bridge Description: US 41 NE over Fahka Union Canal

	Input Parameter	Input Value
NBI Priority Data	State Abbrevation	FL
	Detour Length [miles]	0.6
	Functional Classification	2
	Year Built	1969
	Avg. Daily Traffic	2100
	Structure Length [feet]	219.2
	Deck Width [feet]	420
	Substructure Condition	7
	Channel Protection Condition	8
	Waterway Adequacy Condition	8
	Avg. Daily Truck Traffic [%]	11
	Scour Condition (2002 def.)	U
	Is It a High Priority Route?	Yes
Economic Use Data	Car Running Cost [$/mi]	$0.45
	Truck Running Cost [$/mi]	$1.30
	Duration of Detour [days]	365
	Avg. Value of Time [$/hr/adult]	$6.65
	Avg. Occupancy [adult/car]	1.63
	Avg. Value of Truck Time [$/hr/truck]	$22.01
	Avg. Detour Speed [mi/hr]	40
	Probable No. of Fatalaties if Collapse	2
	Fatality Cost [$/casualty]	$500,000
Construction Mitigation Data	Bridge's Est. Remaining Life [yrs]	13
	Are Any Spans > 100 ft Long?	No
	Total Cost of Replacement [$]	$966,630
	Automated Scour Monitoring Cost [$]	$7,000
	Est. Scour Countermeasure Cost [$]	$35,000
	Est. Field Reconnaissance Cost [$]	$6,015
	Est. Scour Evaluation Cost [$]	$10,808

* The report mentioned is the Phase II report for NCHRP project 24-25 entitled "Guidelines for Risk-Based Management of Bridges with Unknown Foundations".

Analysis	Result	
Is it a high priority bridge?	Yes	
Overtopping Frequency:	S	*(Slight; frequency: 11-100 years)*
Scour Vulnerability:	7	*(Good Condition)*
Estimated Annual Probability of Failure (P_A):	0.00025	
Lifetime Probability of Failure ($P_L = 1-[1-P_A]^L$):	0.0032	
Minimum Performance Standard (MPL):	0.0001	
Does the bridge pass the MPL?	No	*(perform foundation reconnaissance)*
Cost of Replacing Bridge:	$ 966,630	
Cost of Running Vehicles on Detour:	$ 249,956	
Cost of Lost Wages/Revenue On Detour:	$ 138,755	
Cost of Lost Life (C_{death}):	$ 1,000,000	
Total Cost of Failure (C_{total}):	$ 2,355,340	*(sum)*
Lifetime Risk of Lost Life ($R_{death} = P_L{}^*C_{death}$):	$ 3,200	
Lifetime Risk of Failure ($R_L = K^*P_L{}^*C_{total}$):	$ 7,537	
Is $C_{ASH} < R_{death}$?	No	*n/a*
Is $C_{CH} < R_L$?	No	*n/a*
Is $(C_{recon} + C_{analysis}) < 0.5^*C_{CH}$?	Yes	*n/a*
Recommended Risk Management Plan:	Perform field reconnaissance to infer the foundation, and perform standard scour analysis before considering countermeasures, closure, or replacement.	

DON'T CHANGE THE FORMULAS ON THIS OR ANY OTHER SHEET! Use the button at the top to enter a new record for any bridge that you want to analyze. Then you can view the scour risk analysis (on this sheet) for any bridge that you have entered by selecting its Bridge ID in the list box in cell B1. See the supplementary "Scour Risk Analysis Tool (Readme).txt" file for more instructions and cautions about using this tool.

Figure 3-19. Risk analysis report developed for NCHRP Project 24-25.

CHAPTER 4

Develop Foundation Tools: How to Compute Life Expectancy Models

In the research leading to development of this guide, various approaches were investigated for estimating life expectancy for a range of highway asset types. The potential methods were gleaned from current practice in not only highway engineering, but many fields that need to measure life expectancy. Methods were evaluated for their realism, policy sensitivity, data requirements, and appropriate precision for the quality of data available. Data sets were obtained from state DOTs to test and validate the methods. The statistical characteristics of the models, including goodness-of-fit and sensitivity to uncertainty, were important considerations.

In this chapter, the best of the methods tested in the research are described in detail. In addition to the criteria used in the research, some additional considerations in selecting methods for this chapter were:

- Transparency (i.e., the ability for transportation agencies to thoroughly understand and replicate the models in their own applications and systems).
- Applicability to all transportation agencies.
- Focus on the estimation of life expectancy, separate from related applications such as deterioration modeling and lifecycle costing.

Chapter 5 provides much more detail on deterioration and lifecycle cost. In Chapter 4, the analysis of asset deterioration is conducted only to the limited extent necessary in order to determine life expectancy, thus keeping the methods as simple as possible. When an agency commits to the level of data collection and analysis necessary for life expectancy analysis, it can accomplish much more by adding some additional detail and analysis to develop deterioration models. Chapter 5 addresses this consideration.

Table 4-1 describes some of the basic decision-making criteria that can be used to select the model types that may have the best fit to a particular agency and application. In many cases, it may be worthwhile to try more than one type of model and compare the results in order to make a final decision on which form to implement.

All of the models described in the table can be developed using a set of data about existing assets in order to quantify future behavior. They all require past condition and performance data, past preservation and replacement activity data, or both. If past replacement data are unavailable or are not indicative of future replacements, then it is necessary to have data that reliably show a condition threshold when replacement would normally be recommended or required. In other words, it is necessary to have a clear definition of end-of-life and reliable data to indicate when that end-of-life criterion was observed. If the data support it, the analyst can experiment with different definitions of end-of-life to investigate policy sensitivity.

It is important at all times to ensure that the life expectancy or deterioration model is not biased by past maintenance, repair, and rehabilitation activity. When a model requires time-series data,

Table 4-1. Guidelines for selecting the most appropriate model type.

Method of determining life expectancy	When used, implications	Section
Wait for extreme events	Replacement when required due to damage. In some cases historical records may provide guidance on the probability of future hazards.	3.2.1
Determine date of changes in standards	Develop a plan for system-wide upgrades or replacements of affected assets. May drive the selection of life extension activities as a stop-gap in place of replacement for facilities that otherwise might be replaced earlier.	3.2.1
Determine date of changes in functional requirements (e.g., traffic or route changes)	Once the date of the change in requirements is known, affected facilities may have a firm end-of-life. May drive the selection of life extension activities in place of replacement, for facilities that otherwise might be replaced earlier.	3.2.1
Life expectancy models (Chapter 4)		
Published data on life expectancy or replacement interval	Used when it is impossible or uneconomical for the agency to develop its own data and models. Subject to substantial error, caused by unique site characteristics. At the network level, this may drive bulk procurement decisions. At the project level, it may determine individual asset replacements on an interval basis when condition data are unavailable.	4.1
Ordinary regression of age at replacement	Used when replacement records are available and condition/performance data are not available. May be unreliable unless the reasons for historical replacements are known. At the network level, this may drive bulk procurement decisions. At the project level, it may set individual asset replacements on an interval basis when data are unavailable.	4.2.1
"Quick-and-dirty" Markov model	Used when condition data are available and a condition threshold or state can be determined where replacement is commonly recommended or required. Recognizes just two states: failed and not-failed. The data set can be cross-sectional (does not have to follow each asset through its whole life) and must have pairs of inspections before and after a more or less uniform time interval (usually 1-2 years). At the network level, can be used to establish budgets and replacement quantities within a given time horizon. At the project level, replacement occurs when the failed state is observed.	4.2.2
Weibull survival probability model	Similar to Markov model with the same applications but provides a better measure of the effects of age and uncertainty. Requires time series condition data (following each asset through its whole life to detect unreported repair activity) or knowledge of past life extension activity. Can be used to optimize the timing of blanket replacement projects (e.g., all the signs on a corridor). Includes Kaplan-Meier models.	4.2.3
Cox survival probability model	Similar to the Weibull model but allows the effect of explanatory variables to be built right into the model (rather than developing separate Weibull models for separate classes of assets). Useful when explanatory variables are continuous, or when the size of the historical data set is too small to provide the desired resolution with Weibull models.	4.2.4
Deterioration models (Chapter 5)		
Ordinary regression of condition or performance as a deterioration model	Requires continuous (i.e., not discrete) condition data in a time series. Used when uncertainty range is narrow or not relevant. Can indicate end-of-life when condition is forecast to pass a given threshold. May be used for programming of projects for constructed facilities, especially pavements.	5.1.1
Markov deterioration model	Similar to the "quick-and-dirty" Markov model but more precise because it is used with more than two condition states. At the network level, can be used to establish budgets and quantities for replacement and life extension actions within a given time horizon. At the project level, replacement occurs when the failed state is observed.	5.1.2
Markov/Weibull hybrid deterioration model	Similar to the Markov model, but provides more resolution on the onset of deterioration. Requires knowledge of past preventive maintenance activity. Used in the planning of preventive maintenance programs and for generating more accurate network-level condition forecasts.	5.1.3
Ordered probit deterioration model	Provides a condition state-based deterioration model similar to the Markov model but quantifies the level of uncertainty and provides sensitivity to age and other explanatory variables for every condition state. Requires time series condition state inspection data or full knowledge of past work history on each asset and is relatively difficult to estimate. Provides maximum precision for network-level budgeting of life extension activities and replacement.	5.1.4
Machine learning	Commercial "black box" applications to identify relationships among collected data items. Not addressed in this guide.	5.1.5

this also usually means that it is necessary to know for sure that no work was done during the asset's life. When a model requires cross-sectional data in the form of inspection pairs, it is still necessary to know that no work was done between the two inspections in each pair. Often this has to be determined by looking for improvements in condition between inspections.

As discussed in this guidebook, selection of a modeling technique can be made based on the general approach, nature of the dependent variable, preference for a probabilistic or deterministic method, and data type and size.

4.1 Example Life Expectancy Models

The research that contributed to the preparation of this guide quantified a set of life expectancy models to fit the data sets available to the researchers at the time of the study for various asset types. Table 4-2 summarizes the results, which are then described in the remaining parts of this section.

These models reflect only specific agencies and might not be a good fit to other agencies. Before using these models, compare the characteristics of the source agencies and highway networks, including climatic conditions and operating practices, to make sure the models are suitable. The project Final Report contains detailed background information to help in this evaluation.

4.1.1 Culverts

Culverts are most frequently provided as passages for water to flow across or along roadways. However, they may also be provided as means of passage for wildlife on low-volume roads.

4.1.1.1 Measuring Condition and Performance

Markow (2007) and Wyant (2002) reported that most of the states have formal culvert inspection programs. However, states differ in the types of data gathered and retained in databases, the frequency of inspection, and the sizes and types of culverts addressed (Figure 4-1).

FHWA has published culvert inspection guidelines in Arnoult (1986) which provide backup guidance for NBI Item 62, Culvert Condition (FHWA 1995). The collection of this data item is mandatory for all culverts in the United States that are under roads, open to the public, and

Table 4-2. Summary of example models.

Asset type	Typical life	End-of-life*	Method used
Pipe culverts	87 years	Age when 50% probability of failed state	Weibull or Markov
Box culverts	47	Age when 50% probability of failed state	Markov
Traffic signs	12	Age when 50% probability of failed state	Markov
Traffic signals	13	Historical replacement interval	Weibull survival
Roadway lighting	65	Historical replacement interval	Weibull survival
Pavement markings (1A Waterborne Yellow)	2.2	Age when retroreflectivity reaches 65 mcd/sq.m/lux (for yellow markings)	Weibull survival
Pavements (Resurfacing)	12	Age when IRI reaches 220	Markov

See Table 4-23 for full bridge element life predictions.
* for purposes of illustration only.

***Figure 4-1. Culverts of less than 20 feet in span are routinely inspected in many states** (http://www2.dot.ca.gov/hq/oppd/dib/dib83-01-4.htm).*

spanning at least 20 feet. Many agencies also collect the same data for smaller culverts, in some cases as small as 6 feet in diameter (Markow 2007). Table 4-3 shows the definitions that are used.

In addition, more than 40 states use AASHTO CoRe Elements 240-243 (culverts made of unpainted steel, concrete, wood, and other materials, respectively) to describe the condition of culverts in more detail (AASHTO 2002, Thompson 2006). This level of detail is widely used for maintenance planning. It is usually collected for the same culverts that are subject to the agency's routine NBI inspections, including those of less than 20 feet in span. However, culverts inspected

Table 4-3. NBI culvert condition definitions (FHWA 1995).

NBI Item 62 – Culvert condition rating
9. No deficiencies.
8. No noticeable or noteworthy deficiencies which affect the condition of the culvert. Insignificant scrape marks caused by drift.
7. Shrinkage cracks, light scaling, and insignificant spalling which does not expose reinforcing steel. Insignificant damage caused by drift with no misalignment and not requiring corrective action. Some minor scouring has occurred near curtain walls, wingwalls, or pipes. Metal culverts have a smooth symmetrical curvature with superficial corrosion and no pitting.
6. Deterioration or initial disintegration, minor chloride contamination, cracking with some leaching, or spalls on concrete or masonry walls and slabs. Local minor scouring at curtain walls, wingwalls, or pipes. Metal culverts have a smooth curvature, non-symmetrical shape, significant corrosion or moderate pitting.
5. Moderate to major deterioration or disintegration, extensive cracking and leaching, or spalls on concrete or masonry walls and slabs. Minor settlement or misalignment. Noticeable scouring or erosion at curtain walls, wingwalls, or pipes. Metal culverts have significant distortion and deflection in one section, significant corrosion or deep pitting.
4. Large spalls, heavy scaling, wide cracks, considerable efflorescence, or opened construction joint permitting loss of backfill. Considerable settlement or misalignment. Considerable scouring or erosion at curtain walls, wingwalls or pipes. Metal culverts have significant distortion and deflection throughout, extensive corrosion or deep pitting.
3. Any condition described in Code 4 but which is excessive in scope. Severe movement or differential settlement of the segments, or loss of fill. Holes may exist in walls or slabs. Integral wingwalls nearly severed from culvert. Severe scour or erosion at curtain walls, wingwalls or pipes. Metal culverts have extreme distortion and deflection in one section, extensive corrosion, or deep pitting with scattered perforations.
2. Integral wingwalls are collapsed, severe settlement of roadway due to loss of fill. Section of culvert may have failed and can no longer support embankment. Complete undermining at curtain walls and pipes. Corrective action required to maintain traffic. Metal culverts have extreme distortion and deflection throughout with extensive perforations due to corrosion.
1. Bridge closed. Corrective action may put back in light service.
0. Bridge closed. Replacement necessary.

by local agencies might not follow the state DOT's procedures in this regard. Table 4-4 shows the definitions of the four condition states used for each type of culvert.

The types of distresses that typically define culvert condition are summarized in AASHTO guidance (AASHTO 2006). Recently the definitions for all AASHTO elements were revised (AASHTO 2010). However, for culverts, the number of condition states and their general meaning did not change significantly enough to affect the life expectancy analysis. Models developed from historical element inspection data should still be valid when the 2010 AASHTO Manual is implemented.

Washington State DOT uses a culvert assessment system that is especially appropriate for smaller culverts. It rates groups of culverts by counting the percentage that are at least 50% filled with dirt and/or debris, on a scale of A-B-C-D-F, using the cutoffs of 2%, 5%, 10%, and 20% respectively (WSDOT 2008). There is no category E in the Washington system. A separate classification is used for catch basins and inlets, with cutoff percentages of 3%, 7%, 15%, and 30% respectively.

4.1.1.2 End-of-Life Criteria

Both the FHWA and AASHTO definitions are discrete scales where discrete choice models of life expectancy are appropriate, as described in Chapter 3. The recommended end-of-life

Table 4-4. AASHTO CoRe Element condition state definitions for culverts (AASHTO 1997).

240 - Unpainted Steel Culvert	**242 - Timber Culvert**
1. The element shows little or no deterioration. Some discoloration or surface corrosion may exist but there is no metal pitting. There is little or no deterioration or separation of seams.	1. The timber and fasteners are in sound condition.
2. There may be minor to moderate corrosion and pitting, especially at the barrel invert. Little or no distortion exists. There may be minor deterioration and/or separation of seams.	2. There may be minor decay and weathering. Corrosion at fasteners and connections may have begun. There is little or no distortion and/or deflection.
3. Significant corrosion, deep pitting, or some holes in the invert may exist. Minor to moderate distortion and deflection may exist. Minor cracking or abrasion of the metal may exist. There may be considerable deterioration and/or separation of seams.	3. There may be significant decay, weathering, and warped or broken timbers. Significant decay and corrosion at fasteners and connections may be evident. Minor to moderate distortion of the culvert may exist.
4. Major corrosion, extreme pitting, or holes in the barrel may exist. Major distortion, deflection, or settlement may be evident. Major cracking or abrasion of the metal may exist. Major separation of seams may have occurred.	4. There may be major decay and many warped, broken, or missing timbers. There is major decay and corrosion at fasteners and connections. Major distortion or deflection of the culvert may exist.

241 - Reinforced Concrete Culvert	**243 - Other Culvert**
1. Superficial cracks and spalls may be present, but there is no exposed reinforcing or evidence of rebar corrosion. There is little or no deterioration or separation of joints.	1. There is little or no deterioration. Only surface defects are in evidence. There are no misalignment problems.
2. Deterioration, minor chloride contamination, minor abrasion, and minor cracking and/or leaching may have begun. There may be deterioration and separation of joints.	2. There may be minor deterioration, abrasion, cracking, and misalignment.
3. There may be moderate to major deterioration, abrasion, extensive cracking and/or leaching, and large areas of spalls. Minor to moderate distortion, settlement, or misalignment may have occurred. There may be considerable deterioration and separation of joints.	3. Moderate to major deterioration, abrasion, cracking, and/or minor to moderate distortion or deflection has occurred.
4. Major deterioration, abrasion, spalling, cracking, major distortion, deflection settlement, or misalignment of the barrel may be in evidence. Major separation of joints may have occurred. Holes may exist in floors and walls.	4. Major cracking, abrasion, distortion, deflection, settlement or misalignment, and/or major deterioration affecting structural integrity may have occurred.

condition for culverts is the age when there is a 50% probability of being in a condition state where replacement is normally recommended. Bridge management systems such as Pontis have built-in procedures that can estimate condition state transition times and life expectancy, using this definition, for any type of structural asset including culverts (Cambridge 2003, Thompson and Sobanjo 2010). These methods are in widespread use (Thompson 2006).

The 50% probability threshold is a network-level criterion, appropriate for decisions about budgeting for example. States do not necessarily replace individual culverts at exactly this point in time. They may replace a culvert sooner when there is another justification besides condition (e.g., a need to widen the road), or they may delay replacement when insufficient funding is available or when preventive maintenance (e.g., flushing or patching) is a possibility for life extension. In other words, network-level and project-level end-of-life may differ.

Federal policy determines a culvert to be structurally deficient, thereby eligible for replacement funding, if its NBI condition rating is 4 or below. However, for the purposes of this analysis, it was assumed that a condition level of 3 is a more common threshold where culvert replacement is considered.

For states using AASHTO CoRe Elements and Pontis, replacement is normally recommended by the lifecycle cost model when a sufficient percentage of the culvert reaches condition state 4. For consistency in the analysis, this percentage is 50% in the results provided here. Lifecycle cost analysis, however, may suggest a different percentage.

4.1.1.3 Life Extension Interventions

About 25% of the states have preventive maintenance programs for culverts, as a means of life extension (Markow 2007). Chapter 5 describes methods to determine the potential increase in life expectancy, using models of deterioration and lifecycle cost. The examples in the current section assume the states' normal preventive maintenance practices, which were not specified in the data set.

4.1.1.4 Published Life Expectancy Values

Markow (2007) provides a table of asset life estimates developed from a survey of transportation agencies. The number of responding agencies and the median estimate in years are reproduced in Table 4-5. These estimates are primarily from expert judgment.

4.1.1.5 Example Analysis

For this study, the model for pipe culverts was developed primarily from Pennsylvania data, with the addition of small amounts of data from Minnesota and Vermont. Given that not all

Table 4-5. Survey of life expectancy estimates for culverts.

Pipe culverts			**Box culverts**		
Material	Count	Life Years	Material	Count	Life Years
Concrete	13	50	Reinforced concrete	15	50
Corrugated metal	16	35	Timber	3	30
Asphalt coated corrugated metal	5	50	Precast reinforced concrete	1	50
Small diameter plastic	7	50	Polyvinyl chloride	1	50
High-density polyethylene	1	50	Aluminum alloy	1	50

(Markow 2007)

states use the NBI or AASHTO inspection conventions, the researchers used a simpler scale consistent with the three states that contributed data:

0: Very poor or serious deterioration, warranting replacement
1: Poor condition
2: Fair; some wear but structurally sound
3: Excellent condition, like new

In this scale, state 0 is assumed to be equivalent to an NBI condition rating of 3 or below, or an AASHTO CoRe Element condition state of 4. The researchers found the following variables to have a significant effect on life expectancy:

- Material
- Coating application
- Type of inlet and outlet
- Temperature
- Precipitation
- Freeze/thaw cycles
- Soil corrosiveness

For larger, box culverts, NBI data were utilized.

Because of the existence of periodic inspections for large culverts, they are perfect candidates for either Weibull survival probability models or Markov models. A later section, "Developing Life Expectancy Models," describes how to develop Weibull or Markov models. The researchers developed separate models for pipe culverts and box culverts, as follows.

Pipe Culverts. A Weibull survival probability model, with regression used to predict the scaling parameter, was found to best fit the collected data having the following functional form:

$$y_{1g} = \exp\left(-1.0 \times (g/\alpha)^{\beta}\right)$$

where y_{1g} is survival probability as a function of age

$g \equiv$ age at which the survival probability is sought, in years
$\beta =$ shape parameter $= 1.064$

and the scaling parameter is given by:

$$\begin{aligned}\alpha = \exp\big(4.754 &+ 0.215 * (1 \text{ if metal culvert, } 0 \text{ otherwise})\\ &- 0.009 * (\text{average annual freeze/thaw cycles})\\ &- 0.142 * (1 \text{ if high soil corrosiveness potential, } 0 \text{ otherwise})\\ &+ 0.071 * (1 \text{ if ditch inlet/outlet, } 0 \text{ otherwise})\\ &+ 0.097 * (1 \text{ if coated, } 0 \text{ otherwise})\\ &+ 0.098 * (\text{normal annual temperature in } {}^\circ\text{F})\\ &- 0.097 * (\text{normal annual precipitation in inches})\big)\end{aligned}$$

The above results suggest that, in the given study area, pipe culverts in a warmer climate, having ditch inlet/outlets, made of a metal material type, and having protection coating have longer service lives. Areas having higher freeze/thaw cycles and precipitation were generally found to experience a shorter life for culverts.

On average, the model calibrated to the collected data would suggest an average life of 87 years for pipe culverts (Figure 4-2).

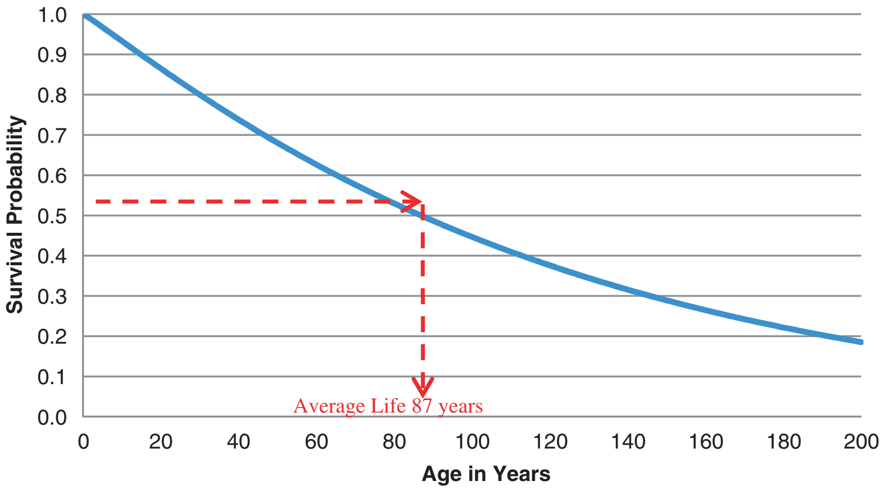


Figure 4-2. Example life expectancy estimate of pipe culverts.

Box Culverts. For the box culverts in the NBI database (see Section 4.1.8 for further details on NBI condition data), a Markov chain model was found to best describe the performance trends. The transition matrices (Table 4-6) were calibrated using the average deterioration curve, which was determined by regressing the age against the condition state. Multiple transition matrices were developed, assuming homogenous deterioration rates within each age group.

The modeling process yielded the survival curve in Figure 4-3. This curve can be interpreted to mean that box culverts are nearly certain to survive up to 30 years but are highly unlikely to survive beyond 54 years without maintenance or rehabilitation. On average, the applied deterioration curve suggests an average life of 47 years.

4.1.2 Traffic Signs

Traffic signs are replaced for various reasons, including the need for, or accuracy of, the information on the sign; evolving standards for legibility, size, or location; physical condition and integrity; impact damage; and retroreflectivity (night visibility). When agencies become aware of a change in the need or the applicable standards, life expectancy becomes a deterministic pro-

Table 4-6. Example transition matrices of box culverts.

	Transition Probability					
Age Group	P(9→8)	P(8→7)	P(7→6)	P(6→5)	P(5→4)	P(4→≤3)
0-6 years	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7-12 years	0.0856	0.0000	0.0000	0.0000	0.0000	0.0000
13-18 years	0.0555	0.1126	0.1202	0.0575	0.0000	0.0000
19-24 years	0.0279	0.0508	0.0855	0.2239	0.0813	0.0000
25-30 years	0.0433	0.0852	0.1158	0.1890	0.1088	0.0000
31-36 years	0.1820	0.1624	0.1308	0.0710	0.0787	0.0530
37-42 years	0.0892	0.2184	0.2762	0.2393	0.1391	0.1161
43-48 years	0.1282	0.1786	0.3031	0.5513	0.7880	0.5128
49-54 years	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

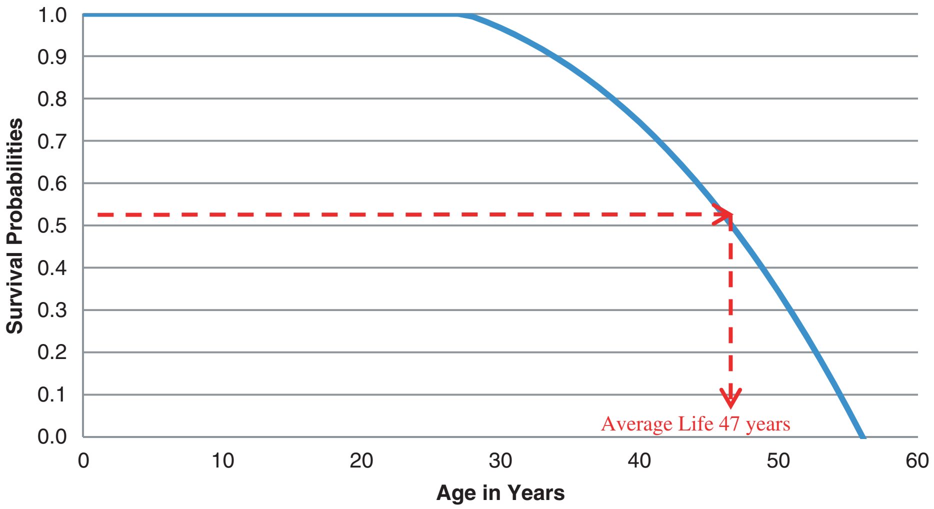


Figure 4-3. Example life expectancy estimate of box culverts.

gramming decision. Therefore, the methods described in this guide focus on condition-based longevity in the absence of changes in the information or standards.

The lifespan of sign sheeting (typically 10 to 15 years) is generally less than that of sign posts and much less than that of sign structures (typically 30 to 50 years) (Figure 4-4). Therefore, these components are not necessarily replaced simultaneously.

4.1.2.1 Measuring Condition and Performance

Markow (2007) reported from a survey of the states, that more than 80% of respondents gather sign condition and performance data using visual inspections. Automated methods of measuring retroreflectivity have been under development, but their routine use is still relatively scarce (Markow 2007). Condition state language of the type used for culverts and bridges has not been developed for sign sheeting or posts, but it is becoming common for sign structures. Condition monitoring of sign sheeting and posts is typically performed by a drive-by assessment

Figure 4-4. Traffic signs include sheeting, posts, and support structures *(http://ops.fhwa.dot.gov/publications/manag_demand_tis/travelinfo.htm).*

during the day and at night. Condition monitoring of sign structures is increasingly done by bridge inspectors, often using hands-on procedures that look for fatigue cracking.

FHWA has established minimum retroreflectivity standards, which are published in the *Manual on Uniform Traffic Control Devices* (MUTCD). Retroreflectivity is the ability of a sign to reflect the light from vehicle headlamps back to the driver's eyes. It is measured in candelas per lux per square meter. Table 4-7 shows the standards (FHWA 2007). When inspections are conducted visually, FHWA recommends that the inspectors begin their nighttime shifts by viewing calibration signs under controlled conditions to improve the accuracy of judging retroreflectivity.

Sign replacement is typically warranted when physical damage or loss of retroreflectivity render the sign insufficiently legible (AASHTO 2006). Most often, in practice, legibility is a matter of judgment by field personnel. The types of damage typically noted are bullet holes, large dents, impact damage, dirt or sap accumulation, graffiti, vandalism, cracking, curling, pitting, edge lifting, blistering, color fading, weathering, and missing reflective material including missing letters.

None of the releases of the AASHTO CoRe Element guides (AASHTO 1997, 2002, and 2010) have addressed sign structures. However, some of the states have developed analogous inspection manuals. Table 4-8 shows the condition state language used by Colorado, and Table 4-9 shows the Florida language.

4.1.2.2 End-of-Life Criteria

For the purpose of modeling life expectancy at the network level, the relevant end-of-life criterion for sign sheeting is the age when 50% of the signs in a given class or population become insufficiently legible or violate federal minimum retroreflectivity standards, thus requiring replacement. For sign structures, a 50% probability of condition state 5 in both the Colorado and Florida manuals would be appropriate, since those are the levels where the Pontis lifecycle cost analysis recommends replacement. Typically, at the project level, the end-of-life criterion would be the point where the individual sign violates minimum standards.

For sign posts, the end-of-life criterion could be similar to that used for sign structures, even though none of the states have a routine inspection program for sign posts. Or more simply, the replacement criterion could be any set of conditions under which a maintenance engineer would recommend replacement.

Table 4-7. Federal minimum retroreflectivity standards (FHWA 2007).

Sign color	**Additional criteria**	**Sheeting Type (ASTM D4956-04)** See note (1)			
		Beaded Sheeting			Prismatic Sheeting
		I	II	III	III to X
White on green	Overhead	W*; G ≥ 7	W*; G ≥ 15	W*; G ≥ 25	W ≥ 250; G ≥ 25
	Ground-mounted	W*; G ≥ 7	W ≥ 120; G ≥ 15		
Black on yellow or black on orange	See note (2)	Y*; O*	Y ≥ 50; O ≥ 50		
	See note (3)	Y*; O*	Y ≥ 75; O ≥ 75		
White on red	See note (4)	W ≥ 35; R ≥ 7			
Black on white		W ≥ 50			

1 The minimum maintained retroreflectivity levels shown in this table are in units of cd/lx/m2 measured at an observation angle of 0.2 ° and an entrance angle of -4.0 °.

2 For text and fine symbol signs measuring at least 1200 mm (48 inches) and for all sizes of bold symbol signs.

3 For text and fine symbol signs measuring less than 1200 mm (48 inches).

4 Minimum Sign Contrast Ratio ≥ 3:1 (white retroreflectivity ÷ red retroreflectivity).

* This sheeting type should not be used for this color for this application.

Table 4-8. Colorado sign structure condition state definitions (LONCO 2007).

620 –Steel Column	622- Concrete Column
1. There is little or no corrosion or misalignment of the member(s). Handhole covers and column caps are in place.	1. The unit shows no deterioration. There may be discoloration, efflorescence, and/or superficial cracking but without effect on strength and/or serviceability.
2. Surface rust, surface pitting, has formed or is forming. There may be minor collision damage that does not warrant addressing it in the traffic impact smart flag. Handhole covers or column caps are missing.	2. Minor cracks and spalls may be present but there is no exposed reinforcing or surface evidence of rebar corrosion.
3. Steel has measurable section loss due to corrosion but does not warrant structural analysis. There is moderate collision damage that warrants implementing the Traffic Impact Smart Flag. Standing water may be observed on the inside of the column. The column is out of plumb.	3. Some delamination and/or spalls may be present and some reinforcing may be exposed. Corrosion of rebar may be present but loss of section is incidental and does not significantly affect the strength and/or serviceability of the element.
4. Corrosion is advanced. Section loss, or collision damage, is sufficient to warrant structural analysis.	4. Advanced deterioration. Corrosion of reinforcement and/or loss of concrete section is sufficient to warrant analysis to ascertain the impact on the strength and/or serviceability of the element.
5. Deterioration is so severe that structural integrity is in doubt. A CIF notification is warranted.	5. Deterioration is so severe that the structural integrity of the column is in doubt. A CIF notification is warranted.

621- Prestressed Concrete Column	640 - Frame/Mast Arm
1. The unit shows no deterioration. There may be discoloration, efflorescence, and/or superficial cracking but without effect on strength and/or serviceability.	1. There is no evidence of active corrosion on metal. The paint system is sound and functioning as intended to protect the metal surface. Weathering steel is coating uniformly and is in excellent condition.
2. Minor cracks and spalls may be present and there may be exposed reinforcing but no evidence of corrosion. There is no exposure of the prestress system.	2. There is little or no active corrosion on the metal. Surface or freckled rust has formed or is forming. The paint system may be chalking, peeling, curling or showing other early evidence of paint system distress but there is no exposure of metal.
3. Some delamination and/or spalls may be present. There may be minor exposure but no deterioration of the prestress system. Corrosion of non-prestressed reinforcement may be present but loss of section is incidental and does not significantly affect the strength and/or serviceability of the element.	3. Corrosion is prevalent on the metal with 10% to 20% section loss. The paint system, if present, is no longer effective.
4. Delamination, spalls, and corrosion on non-prestressed reinforcement are prevalent. There may also be exposure and deterioration of the prestress system (manifested by loss of bond, broken strands or wire, failed anchorages, etc). There is sufficient concern to warrant an analysis to ascertain the impact on the strength and/or serviceability of the element.	4. Corrosion is prevalent on the metal with 20% to 30% section loss but does not warrant structural analysis of the element.
5. Deterioration is so severe that the structural integrity of the column is in doubt. A CIF notification is warranted.	5. Corrosion is advanced with section loss greater than 30%. The paint system, if present, has failed. Structural analysis is warranted to ascertain the impact on the ultimate strength and/or serviceability of the element. A CIF notification is required.

Because of mobilization and traffic control costs, there are economies of scale in replacing all signage along a roadway at the same time (blanket replacement). As a result, a lifecycle cost analysis may result in a shorter optimal life expectancy with fewer than 50% of the assets reaching the end-of-life criterion. This would be relevant to states that have blanket replacement policies or are considering implementing them.

4.1.2.3 *Life Extension Interventions*

About half of the states have some sort of preventive maintenance program for signage (Markow 2007). Life extension activities include washing, at intervals from 1 to 5 years, and

Table 4-9. Florida sign structure condition state definitions (Florida DOT 2010).

487 - Overlane Sign Structure Horizontal Member	488 - Overlane Sign Structure Vertical Member
1. There is no evidence of active corrosion and the coating system is sound and functioning as intended to protect the metal surface.	1. There is no evidence of active corrosion and the coating system is sound and functioning as intended to protect the metal surface.
2. There is little or no active corrosion. Surface corrosion has formed or is forming. The coating system may be chalking, peeling, curling or showing other early evidence of paint system distress but there is no exposure of metal.	2. There is little or no active corrosion. Surface corrosion has formed or is forming. The coating system may be chalking, peeling, curling or showing other early evidence of paint system distress but there is no exposure of metal.
3. Surface corrosion is prevalent. There may be exposed metal but there is no active corrosion which is causing loss of section.	3. Surface corrosion is prevalent. There may be exposed metal but there is no active corrosion which is causing loss of section.
4. Corrosion may be present but any section loss due to active corrosion does not yet warrant structural review of the element.	4. Corrosion may be present but any section loss due to active corrosion does not yet warrant structural review of the element.
5. Corrosion has caused section loss and is sufficient to warrant structural review to ascertain the impact on the ultimate strength and/or serviceability of the unit.	5. Corrosion has caused section loss and is sufficient to warrant structural review to ascertain the impact on the ultimate strength and/or serviceability of the unit.

repairs to damaged posts and panels. For painted sign structures, painting is often performed as a preventive maintenance activity. Certain sign structures are subject to fatigue damage, for which the agency may have countermeasures. The data available to the researchers of the NCHRP Project 08-71 study did not distinguish which signs were subject to preventive maintenance programs. This would be a valuable topic for future research. Agencies having this type of maintenance history data could evaluate maintenance effectiveness using the methods in Chapter 5.

4.1.2.4 Published Life Expectancy Values

Substantial data on life expectancy of signs, sign posts, and sign structures were gathered in Markow (2007) from a survey of transportation agencies and from a literature review. This information was determined primarily from expert judgment, with additional information taken from published state standards. The number of responding agencies and the median estimate in years are shown in Table 4-10.

4.1.2.5 Example Analysis

The performance of traffic signs can be modeled using an appropriate performance indicator such as the retroreflectivity of the sign sheeting. Retroreflectivity is measured in units that represent a continuous variable. For this study, data from the National Transportation Product Evaluation Program (NTPEP) were used, which were gathered from various test sites located in

Table 4-10. Survey of life expectancy estimates for sign components (Markow 2007).

Sign sheeting			Sign posts			Sign structures		
Type	Count	Life	Type	Count	Life	Type	Count	Life
All sheeting	17	10	Steel U-channel	10	15	Steel sign bridge	12	30
Aluminum	3	11	Steel square tube	10	15	Aluminum sign bridge	8	30
Vinyl	2	6	Steel round tube	3	15	Overpass bridge mounting	1	50
Types I-II	Literature	5-7	Aluminum tube	1	10			
Types III-IV	Literature	10-15	Wood	3	15			
Types V-X	Literature	15-20	Structural steel beam	2	27.5			

different states. To determine asset life, a Markov chain can be calibrated to estimate the transition probability of traffic signs progressing from a subjective rating of "good" to "fair" and ultimately "poor." Alternatives to sign sheeting retroreflectivity, such as physical deterioration of sign structure, lack of color/contrast of sign sheeting, and blistering, cracking and shrinkage of sign sheeting materials, can be duly assessed. The Markov model in Table 4-11 considers the "poor" stage as the end-of-life condition, while the "good" stage is the initial condition.

The transition matrix was calibrated according to the average deterioration curve, based on a regression of asset age against condition state. The survival curve in Figure 4-5 suggests that the average life of traffic signs is about 12 years and that similar signs are unlikely to last beyond 30 years.

4.1.3 Traffic Signals

Traffic signal systems and Intelligent Transportation Systems (ITS) provide traffic control and communication with drivers and vehicles. For asset management purposes, the systems are made up of signal heads, flashers, detectors, controllers, support structures, enclosures, communications equipment, and other electronic components.

Traffic signal components are often replaced based on their condition but are replaced sometimes based on improvements in technology. Signal heads and flashers contain lamps that are typically replaced on an interval basis (often 12 or 18 months), with long intervals for modern LED lamps (5 years or more). Often they are mounted on mast arm structures that are inspected by transportation agencies in the same manner as sign structures.

Table 4-11. Example transition matrix for simple Markov model of traffic signs.

To condition state: From condition state:	Good	Fair	Poor
Good	0.8949	0.1051	0
Fair	0	0.8277	0.1723
Poor	0	0	1.0000

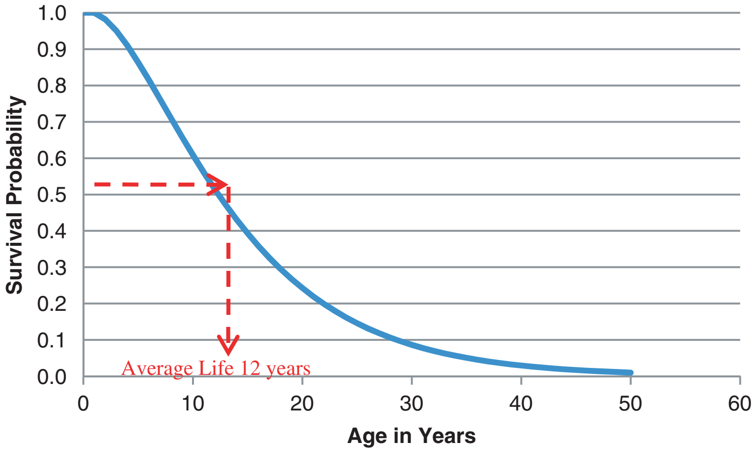


Figure 4-5. Example life expectancy estimate of traffic signs.

4.1.3.1 Measuring Condition and Performance

Agencies typically inspect key components annually and/or when relamping (Markow 2007). More than 70% of transportation agencies maintain an inventory of traffic signal components, and about ⅓ of agencies maintain component condition data. There are no published standards for formal visual inspections of most signal components, except structural supports, so relatively informal methods, such as good-fair-poor, are often used.

Traffic signal system repairs are often driven by operational requirements and become more frequent as the components age. This insight is behind the performance rating system used by Washington State DOT (WSDOT 2008). The system rates each signal system on a scale of A-B-C-D-F (omitting E), based on the frequency of repair. The repair frequencies corresponding to the letter grades are one per 2 years, one per year, two per year, three per year, and four per year, respectively. WSDOT has a similar scheme for ITS equipment.

For poles, mast arms, and other structures that make up the structural support of traffic signal heads and flashers, many states perform routine inspections that are similar to their procedures for sign structures. The preceding section presents the definitions used by Colorado and Florida for this purpose.

4.1.3.2 End-of-Life Criteria

For signal heads, flashers, detectors, controllers, communications equipment, and other electronic components, an appropriate end-of-life condition would be a condition state so deteriorated that no economical repair option is available or, as in the WSDOT case, an excessive repair frequency. This is separate from concerns about technological obsolescence, which would not be analyzed in the same way as deterioration. If an agency has developed replacement warrants based on condition, then these might form the basis of end-of-life criteria. For a population of traffic signals, life expectancy could be the age when there exists a 50% probability that a given asset needs to be replaced.

For structural supports, the end-of-life condition would most appropriately correspond to condition state 5 in sign structure elements as presented for Colorado and Florida in the preceding section of this guide.

Because of mobilization and traffic control costs and technological compatibility, there are economies of scale in replacing all signal equipment at an intersection, or even along a whole section of road, at the same time (blanket replacement). As a result, a lifecycle cost analysis may result in a shorter optimal life expectancy with fewer than 50% of the assets reaching the end-of-life criterion.

4.1.3.3 Life Extension Interventions

About 50% of agencies have some form of preventive maintenance program for traffic signals (Markow 2007). A significant portion is driven by operational problems noted by crews or the public. Repairs that are performed during or after inspections respond to damage that is observed, such as corrosion, loose connections, non-functioning components, damaged wiring or insulation, and accumulated debris. Typically, if such problems are not addressed, operational failures may result. Given that most repair and rehabilitation activities are either driven by operational concerns or involve replacement of components, they are not considered life extension interventions for the purpose of this analysis (Harrison et al. 2004).

4.1.3.4 Published Life Expectancy Values

Data on the life expectancy of traffic signal components were gathered in Markow (2007) from a survey of transportation agencies. This information was provided primarily from expert judgment. Table 4-12 summarizes the number of responding agencies and the median estimate in years for each component.

Table 4-12. Survey of life expectancy estimates for signal components (Markow 2007).

Structural components			**Controller system components**			**Signal display components**		
Type	Count	Life	Type	Count	Life	Type	Count	Life
Tubular steel mast arm	14	20	Permanent loop detector	14	7.5	Incandescent lamps	15	1
Tubular aluminum mast arm	7	20	Non-invasive detector	12	10	Light-emitting diode lamps	18	6.5
Wood pole (and span wire)	9	15	Traffic controller	18	15	Signal heads	15	20
Concrete pole (and span wire)	2	12.5	Traffic controller cabinet	17	15	Pedestrian displays	1	15
Steel pole (and span wire)	9	20	Twisted copper interconnect cable	11	20			
Galvanized pole and span arm	1	>100	Fiber-optic cable	7	20			

Minnesota DOT noted that a life expectancy of 30 years is plausible for electronic components in the signal cabinet when a preventive maintenance program is in place.

4.1.3.5 Example Analysis

The data collection aspect of this research suggests that few agencies track the deterioration of their traffic signals and flashers. However, agencies in Missouri, Oregon, and Pennsylvania were able to provide data on traffic controller deactivation intervals. With such data, an interval-based approach was used to develop the life expectancy models, and it was found that the following variables significantly affect the life expectancy of this asset type:

- Temperature
- Mounting structure
- Wind speed
- Roadway functional class
- Control type

A parametric model was developed for existing assets, assuming the control type served as a proxy for age. Merely installing a new signal of a certain control type does not cause life to be extended. Thus, a Weibull-distributed survival probability model can be developed for existing traffic signals as follows:

$$y_{1g} = \exp\left(-1.0 \times (g/\alpha)^{\beta}\right)$$

where y_{1g} is survival probability as a function of age

$g \equiv$ age the survival probability is sought for in years
$\beta =$ the shape parameter, 1.415 and

the scaling parameter is given by:

$$\begin{aligned}\alpha = \exp\big(9.343 &- 0.101 * (\text{average wind speed in mph})\\ &- 0.108 * (\text{average annual temperature in °F})\\ &+ 0.139 * (\text{1 if pre-timed or semi-actuated signal, 0 otherwise})\\ &- 0.288 * (\text{1 if on a city street, 0 otherwise})\\ &- 0.583 * (\text{1 if supported by a mast arm, 0 otherwise})\\ &+ 0.352 * (\text{1 if part of a closed loop or hardwire interconnected})\\ &- 0.319 * (\text{1 if fiber-optic cables, 0 otherwise})\big)\end{aligned}$$

The example analysis suggests that pre-timed or semi-actuated traffic signals that were hardwire interconnected or part of a closed loop tend to have longer service lives. On the other hand, signals located in warmer climates, areas with higher wind speeds, located on city streets, supported by a mast arm, or with fiber-optic cables tended to have shorter service lives. On average, the calibrated model indicated an average life of 13 years (Figure 4-6).

In the data provided by the agencies, there was no indication of the rationale for replacing a traffic signal controller. Therefore, it can be surmised that various factors besides physical degradation may have led to its replacement, such as the possible need to synchronize the timing of replacement of similar asset types. In this example application of life expectancy estimation techniques, physical deterioration was assumed to be the cause of replacement. However, in practice, agencies should discern the actual reason for replacement so that life expectancy can be estimated more reliably.

4.1.4 Roadway Lighting

Roadway lighting provides safety, comfort, and aesthetic benefits to the public. However, agencies have had difficulty in developing routine condition assessment processes due to the large number of fixtures and relatively low cost of each fixture. This makes lighting a good candidate for sample-based inspection.

4.1.4.1 Measuring Condition and Performance

Most agencies have an inventory of roadway lighting, but few maintain a database of the condition of lighting components. Although lighting units are inspected annually by most agencies, the data resulting from such inspections are in the form of work orders for repairs that may be needed (Markow 2007). Thus, data for estimation of life expectancy are very scarce for most lighting components. Table 4-13 shows an example where the condition state concept used for culverts and sign structures has been applied to lighting.

One area where data are more commonly available is high-mast light poles. Due to incidents where fatigue or corrosion has caused pole failure, many agencies have begun gathering high-mast light pole data as a part of the structure inspection program. As a result, data on the condition of these assets are more readily available. Table 4-14 shows condition state language used in Florida to inspect high-mast light poles.

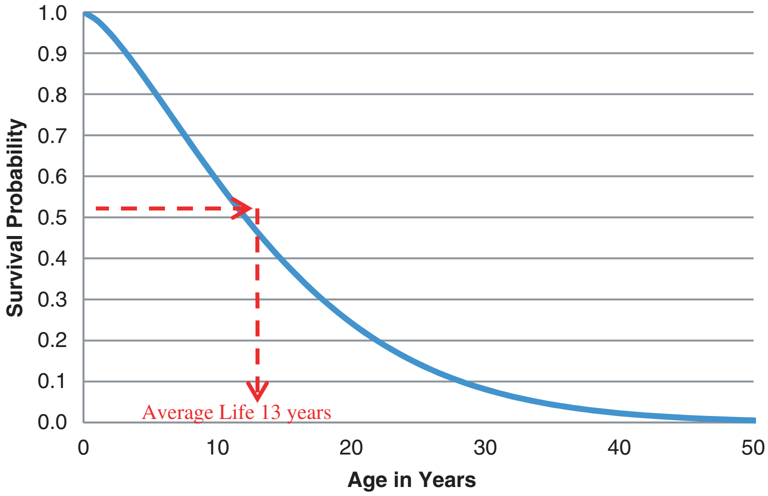


Figure 4-6. Example life expectancy estimate of traffic signal controllers.

Table 4-13. Example of condition state language for lighting (Virginia).

703 – Lighting
1. Lighting standards and supports are properly anchored. There are no indications of fatigue damage. There are no missing or broken luminaires or exposed wires.
2. Lighting standards and supports are properly anchored. There are no indications of fatigue damage. There may be some missing or broken luminaires, but there are no exposed wires.
3. Lighting standards and supports are properly anchored. There may be some indications of fatigue damage. Luminaires may be missing or broken, but there are no exposed wires.
4. Lighting standards and supports may be improperly anchored. There may be indications of fatigue damage. Luminaires may be missing or broken, or there may be exposed wires.

Table 4-14. High-mast light pole condition states (Florida 2010).

495 - High-Mast Light Poles Metal Uncoated	498 - High-Mast Light Poles Other Material
1. There is little or no corrosion of the unpainted steel. The weathering steel is coated uniformly and remains in excellent condition. Oxide film is tightly adhered.	1. There is little or no deterioration. Surface defects only are in evidence.
2. Surface corrosion, surface pitting, has formed or is forming on the unpainted steel. The weathering steel has not corroded beyond its design limits. Weathering steel color is yellow orange to light brown. Oxide film has a dusty to granular texture.	2. There may be minor deterioration, cracking and weathering. Mortar in joints may show minor deterioration.
3. The steel has measurable section loss due to corrosion but does not warrant structural review. Weathering steel is dark brown or black. Oxide film is flaking.	3. Moderate to major deterioration and cracking. Major deterioration of joints.
4. Corrosion is advanced. Oxide film has a laminar texture with thin sheets of corrosion. Section loss is sufficient to warrant structural review to ascertain the impact on the ultimate strength and/or serviceability of either the element or the bridge.	4. Major deterioration, splitting, or cracking of materials may be affecting the structural capacity of the element.

497 - High-Mast Light Poles Galvanized (or Painted)	499 - High-Mast Light Pole Foundations
1. There is no evidence of active corrosion and the coating system is sound and functioning as intended to protect the metal surface.	1. The element shows little or no deterioration. There may be discoloration, efflorescence, and/or superficial cracking but without affect on strength and/or serviceability.
2. There is little or no active corrosion. Surface corrosion has formed or is forming. The coating system may be chalking, peeling, curling or showing other early evidence of paint system distress but there is no exposure of metal.	2. Minor cracks and spalls may be present but there is no exposed reinforcing or surface evidence of rebar corrosion.
3. Surface corrosion is prevalent. There may be exposed metal but there is no active corrosion which is causing loss of section.	3. Some delamination and/or spalls may be present and some reinforcing may be exposed. Corrosion of rebar may be present but loss of section is incidental and does not significantly affect the strength and/or serviceability of either the element or the bridge.
4. Corrosion may be present but any section loss due to active corrosion does not yet warrant structural review of the element.	4. Advanced deterioration. Corrosion of reinforcement and/or loss of concrete section and/or settlement or rotation of foundations are sufficient to warrant review to ascertain the effect on the strength and/or serviceability of either the element or the bridge.
5. Corrosion has caused section loss and is sufficient to warrant structural review to ascertain the impact on the ultimate strength and/or serviceability of the unit.	

4.1.4.2 End-of-Life Criteria

For electrical components and luminaires, an appropriate end-of-life condition would be a condition state so deteriorated that no economical repair option is available or, similar to Washington State's treatment of traffic signals, an excessive repair or relamping frequency. This is separate from concerns about technological obsolescence, which would not be analyzed in the same way as deterioration. If an agency has developed replacement warrants based on condition, then these might form the basis of end-of-life criteria.

For high-mast light poles, an appropriate end-of-life condition would be the worst-defined condition state in a visual inspection such as shown for Florida.

For a population of lighting assets, the life expectancy would be the age when 50% of the population is in need of replacement according to these criteria. Lifecycle cost analysis may reduce the optimal percentage dramatically because of the mobilization and traffic control costs of lighting asset replacement. This is why the practice of group relamping is very common. Similar considerations apply to repairs and replacement. Agencies will normally tolerate a small number of failures before mobilizing to perform relamping and repair on a segment of road.

However, if the failure rate becomes excessive, such that normal relamping intervals are insufficient, then replacement may become economical even if most of the fixtures are still operational. Thus the optimal life expectancy of a group of lights along a roadway may be less than the lifespan of the individual fixtures considered in isolation.

4.1.4.3 Life Extension Interventions

Markow (2007) noted that life extension possibilities may exist for control cabinets and switchgear by means of cleaning, adjustment, and protection. Luminaires and lamps, however, rarely receive any sort of life extension action. Certain types of light poles can have their lives extended by painting.

4.1.4.4 Published Life Expectancy Values

Data on the life expectancy of roadway lighting components were gathered in Markow (2007) from a survey of transportation agencies. This information is primarily from expert judgment. Table 4-15 summarizes the number of responding agencies and the median estimate in years, for each component.

4.1.4.5 Example Analysis

Data from a relatively small sample of historical lighting fixtures' deactivation records were obtained from Missouri for this part of the study. Due to the small size of the sample, the example herein uses a non-parametric Weibull probability model (Figure 4-7):

Table 4-15. Survey of life expectancy estimates for lighting components (Markow 2007).

Structural components			**Lamps**			**Other components**		
Type	Count	Life	Type	Count	Life	Type	Count	Life
Tubular steel	12	25	Incandescent	3	1	Ballast	9	7.5
Tubular aluminum	9	25	Mercury vapor	6	4	Photocells	11	5
Cast metal	2	22.5	High-pressure sodium	15	4	Control panels	7	20
Wood posts	2	32.5	Low-pressure sodium	3	4	Luminaires	2	16.25
High-mast or tower	11	30	Metal halide	9	3			
			Fluorescent	1	5			

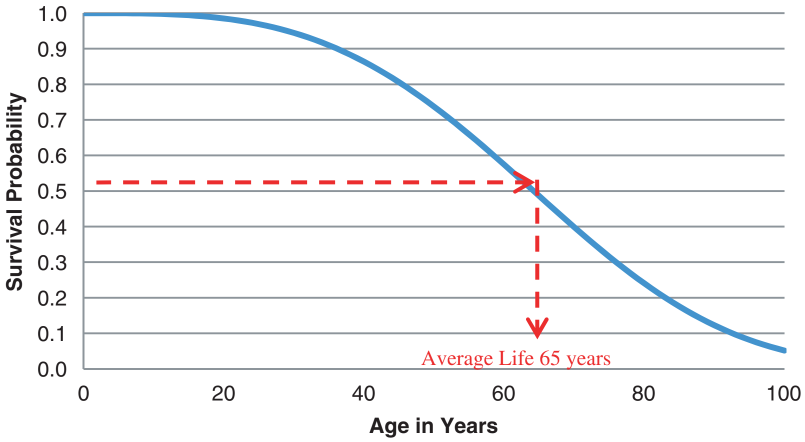


Figure 4-7. Example life expectancy estimate of roadway lighting fixtures.

$$y_{1g} = \exp\left(-1.0 \times (g/\alpha)^{\beta}\right)$$

where y_{1g} is survival probability as a function of age

$g \equiv$ age at which the survival probability is sought, in years
$\beta =$ shape parameter, 3.281 and
$\alpha =$ scaling parameter, 71.788

On average, the fixtures in the dataset were predicted to survive 65 years. As is the case with traffic signals, the reason for replacement was not available in the dataset. Where an agency possesses data that have adequate observations involving recorded replacement reasons, a survival curve could be fitted for each replacement reason. With the likelihood of each replacement reason, a combined probability curve could be developed using basic probability theory as follows:

$$P(A \cup B) = P(A) + P(B) - P(A \cap B)$$

where Event *A* represents the probability of the asset life being reached due to reason A
Event *B* represents the probability of the asset life being reached due to reason B.

4.1.5 Pavement Markings

Pavement markings include the longitudinal lane, shoulder, and center lines; raised markers; and various symbols, guidance, and warning messages on the surface of the roadway. Because they are frequently in contact with tires, snowplows, precipitation, chemicals, and debris and are subject to direct sunlight, pavement markings deteriorate quickly. Yet they are extremely effective in facilitating safe and efficient travel (FHWA 1994). Replacement decisions are mostly condition-driven but can result from changes in requirements such as relocating lanes or reconfiguring intersections or changes in standards. The example provided for the life expectancy analysis focuses on condition-related replacement.

4.1.5.1 Measuring Condition and Performance

Agencies typically try to calibrate their condition assessment of pavement markings with levels of safety or driver perception. The most common metric is retroreflectivity, the ability of the marking to reflect light from the headlights of a vehicle back to the driver's eyes. Retroreflectivity degrades over time due to wear, ultraviolet and chemical attack, and accumulation of salt, dirt, and debris. Most agencies assess retroreflectivity at least annually and at least visually, but, in some cases, use automated equipment. Agencies also assess the degree of missing or damaged markings and raised markers.

WSDOT rates retroreflectivity on a scale of A-B-C-D-F (omitting E) using the cutoff values of 201, 165, 80, and 30 mcd/sq.m/lux, respectively. WSDOT assesses missing or damaged pavement markers on a section of road using the percentage cutoffs of 5%, 10%, 20%, and 30% respectively. For pavement markings such as stop bars, arrows, and crosswalks, WSDOT counts the percentage of these markings on a section of road that have at least 25% worn or missing. The cutoff percentages are 2%, 10%, 20%, and 40% (WSDOT 2008).

FHWA has established recommended minimum retroreflectivity values for pavement markings, optimized for aged asphalt pavements and passenger cars and maintained for in-service roads (Debaillon et al. 2007). These values are shown in Table 4-16. The recommendations apply to MUTCD-warranted center line and edge line pavement markings, including lane lines on Interstate highways and freeways, measured under dry conditions in accordance with the 30-m (98.4-ft) geometry described in ASTM E1710. The reduction factor recommended for raised reflective pavement markers (RRPMs) assumes that the RRPMs are in good working condition and that at least three of them are visible to nighttime drivers at any point along the road. On two-lane highways with RRPMs along the center line only, the reduction factor applies to both center lines and edge lines.

Yellow lines, when new, have lower retroreflectivity than white lines. Since the two colors deteriorate at about the same rate, yellow pavement markings are seen in practice to have a shorter asset life. Some states compensate by establishing a replacement threshold for white markings that is 20% higher than for yellow (Markow 2007).

4.1.5.2 End-of-Life Criteria

For the example analysis, the end-of-life criterion is the age when there is a 50% probability of reaching level F (using the Washington State definitions) or violating the federal recommended minimum retroreflectivity levels. Most states make pavement marking decisions based on condition, rather than life expectancy, so the 50% level is appropriate for budgeting decisions. If life expectancy is to be used as the asset-level replacement criterion (without measuring actual retroreflectivity), then the probability threshold should be set lower. This change would yield a lower probability of violating the minimum standard and a shorter asset life. This is a case where effective performance measurement translates directly to life extension and cost savings.

4.1.5.3 Life Extension Interventions

Agencies commonly perform routine street cleaning to remove dirt, film, and debris from the road surface and improve the visibility of pavement markings. For the example analysis, data on the frequency of street cleaning were not available. Agencies that have this information

Table 4-16. Recommended minimum in-service retroreflectivity of pavement markings.

Roadway marking configuration	Without RRPMs			With RRPMs
	<= 50 mph	55-65 mph	>= 70 mph	
Fully-marked roadways	40	60	90	40
Roadways with center lines only	90	250	575	50

(Debaillon et al. 2007) Retroreflectivity measured in mcd/sq.m/lux. Recommendation applies to both white and yellow.

can perform a lifecycle cost analysis, as in Chapter 5, to determine optimal cleaning intervals to maximize the life expectancy of pavement markings.

4.1.5.4 Published Life Expectancy Values

Data on the life expectancy of pavement markings was gathered in Markow (2007) from a survey of transportation agencies. This information is primarily from expert judgment. Table 4-17 summarizes the number of responding agencies and the median estimate in years, for each type.

The life expectancy of pavement markings can be sensitive to installation quality, winter chemical application, and snow removal practices. Some agencies install markings into a shallow groove in the pavement to prolong the life expectancy.

4.1.5.5 Example Analysis

The life expectancy of pavement markings varies with respect to different factors such as color and marking material type. The following example illustrates the Weibull-distributed survival probability model that was developed on the basis of "1A: 2-year Waterborne yellow markings" data from existing test decks of NTPEP. The skip-retroreflectivity value of 65 mcd/sq.m/lux was taken as the end-of-life performance threshold.

$$y_{1g} = \exp\left(-1.0 \times (g/\alpha)^{\beta}\right)$$

where y_{1g} is survival probability as a function of age

$g \equiv$ the age at which the survival probability is sought, in months.
$\beta =$ shape parameter, 3.87 and

the scaling parameter is given by

$$\begin{aligned}\alpha = \exp\,(1.1 - 0.58 * \text{Orientation}\,(1 \text{ if longitudinal}, 0 \text{ if transverse})\\ - 0.01 * \text{Initial Retroreflectivity value}\\ - 0.29 * \text{Road surface type}\,(1 \text{ if asphalt}, 0 \text{ if concrete}))\end{aligned}$$

The percentiles of survival distribution can be plotted to give an indication of life expectancy. In this case, the plot suggests that 25% of the markings have an asset life of approximately 45 months or more, while 75% of the markings have an asset life of at least 18 months. On average, the calibrated model indicates an average life of 26 months (Figure 4-8).

The marking performance also can be rated using a discrete subjective rating process that may enable the modeler to apply alternative estimation methods such as Markov chains or ordered probit models. A rating scale may be more appropriate than the current continuous rating based on retroreflectivity only given that markings can deteriorate due to abrasion, lack of durability, and lack of contrast.

Table 4-17. Survey of life expectancy estimates for pavement markings (Markow 2007).

Lane and edge striping						Pavement markers		
Type	Count	Life	Type	Count	Life	Type	Count	Life
Non-epoxy paint	22	1 yr	Polyester	2	2.3	Ceramic	2	3
Epoxy paint	13	4	Tape	5	6	Raised	10	3
Thermoplastic	16	4	Thin thermoplastic	1	1-2	Recessed	6	2.5
Cold plastic	8	5	Preformed thermoplastic	1	3	Raised snowplowable	1	4

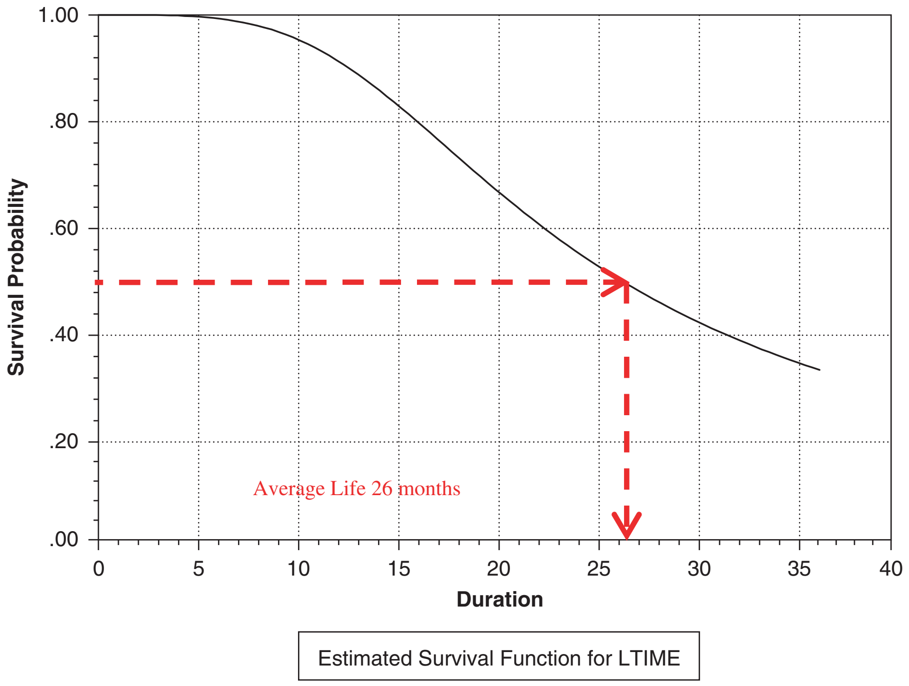


Figure 4-8. Example life expectancy estimate of 1A: 2-yr Water-Based Yellow Pavement Marking.

4.1.6 Curbs, Gutters, and Sidewalks

Curb and sidewalk replacement is often driven by functional stimulus such as changes in requirements, changes in land use, urban betterment projects, or related roadway projects such as widening. Condition-related replacement can occur when movement or deterioration cause the asset to exceed a level-of-service standard for accessibility, driven by concern for lawsuits or compliance with the Americans with Disabilities Act (ADA). In residential areas, aesthetics can also play a significant role in the decision to replace assets of these types.

4.1.6.1 Measuring Condition and Performance

Condition assessment of sidewalks occurs very infrequently, if at all. Most agencies in a recent survey assessed sidewalk condition less often than once every 2 years. Portland, Oregon, for example, with a relatively mature asset management program, performs sidewalk assessments on a 20-year cycle (Markow 2007).

Typically, in many agencies, complaints trigger an inspection, at which time the sidewalk may be evaluated using LOS standards. The sidewalk is replaced if it fails the standards.

4.1.6.2 End-of-Life Criteria

An appropriate network-level end-of-life criterion is the age at which there is a 50% chance that a sidewalk inspection will fail the level-of-service standards over an extensive length. The project-level criterion would be the actual violation of standards over an extensive length.

4.1.6.3 Life Extension Interventions

For isolated cracks or slab movement, agencies have several life extension options available, including crack sealing, mudjacking, tree root removal, drainage improvements, and planing or filling of projections and tripping hazards. Given that both the costs and benefits of these activities are low, life extension decisions are typically made using engineering judgment.

4.1.6.4 Published Life Expectancy Values

Data on the life expectancy of curbs and sidewalks were gathered in Markow (2007) from a survey of transportation agencies. This information is primarily from expert judgment. Table 4-18 summarizes the number of responding agencies and the median estimate in years, for each type.

4.1.6.5 Example Analysis

The New York State Department of Transportation (NYSDOT) is one of the few agencies that has developed basic models for bridge sidewalk fascia deterioration. The agency uses a sidewalk condition rating (CR) on a scale of 0 (worst) to 7 (best). NYSDOT developed the following deterioration model for concrete bridge sidewalks (Agrawal and Kawaguchi 2009):

$$CR = 7 - 0.698\text{E-}1 * (\text{Age}) + 0.190\text{E-}3 * (\text{Age})^2 - 0.4\text{E-}6 * (\text{Age})^3$$

Assuming this deterioration function and an end-of-life criterion of CR = 2, the life of sidewalk fascia design, on the basis of the collected data, is 90 years. The New York study provides similar deterioration curves for other bridge-related elements.

4.1.7 Pavements

Pavements represent the most extensive and expensive asset type in larger transportation agencies. Pavement management systems provide modeling of deterioration and life expectancy, sensitive to the factors that are important to each agency. Such models may distinguish rigid, flexible, and granular traveled surfaces for various categories of traffic and subgrade characteristics. The models may also address shoulders, curbs and sidewalks, medians, barriers, and markings. The wearing surface of a pavement may be replaced separately from the full-depth pavement structure so the surface typically has a shorter life expectancy.

4.1.7.1 Measuring Condition and Performance

Transportation agencies separately measure several aspects of pavement condition, which separately or together may determine the life. Typical quantities measured are

- **Roughness.** Typically using IRI, a measure of deviation from a smooth surface, in inches per mile; or the older PSR, a subjective measure on a scale of 0 to 5. IRI is almost universally used as the most direct measure of the public perception of pavements.
- **Distress.** Depending on the type of pavement, the typical distresses are rutting, transverse cracking, fatigue cracking, longitudinal cracking, map/block/alligator cracking, raveling, faulting, spalling, bleeding, and flushing. In a recent survey of 55 transportation agencies (mostly state DOTs), it was found that each of these distresses is quantified by more than half of the respondents, usually on an annual basis (Flintsch and McGhee 2009).
- **Structural capacity.** A measure of the ability of the pavement structure to carry loads. Only 16% of the respondents in the Flintsch survey routinely gather this information network-wide, but 71% gather it for specific pavement segments as part of project design.
- **Friction.** A measure of safety, the ability of the pavement to support strong braking of vehicles without skidding. The Flintsch survey showed that 34% of respondents gather this information network-wide, and 55% gather it on a project-level basis.

Of the above measures, structural capacity may be the most direct determinant of life expectancy. However, structural capacity data are relatively expensive to collect routinely, and few agencies do so. Among the various distresses, rutting and faulting have the most direct correlation to life expectancy, but any of the distresses can limit life extension possibilities.

Table 4-18. Survey of life expectancy estimates for sidewalks and curbs (Markow 2007).

Sidewalks			**Curbs**			**Corners (urban areas)**		
Type	Count	Life	Type	Count	Life	Type	Count	Life
Concrete	7	25	Concrete	7	20	Concrete curbs	6	20
Asphalt	5	10	Asphalt	2	10	Granite curbs	1	20
Brick or block	2	20	Granite block	1	20	Concrete ramp	4	20
Gravel, crushed rock	1	10				Stone/brick ramp	2	20

In pavement management systems, it is common to combine various distresses into a composite pavement condition rating (PCR) (sometimes called Pavement Quality Index or a state-specific name) as a more convenient measure of structural condition. Each agency has its own way of calculating PCR, sensitive to its own management concerns. In some agencies, roughness, structural capacity, and/or friction may be included in the PCR. Very often, but not always, PCR is on a scale of 0-100 with 100 being like-new condition (Flintsch and McGhee 2009).

Another approach, which works for multiple pavement distresses, is to add the lane-feet of any type of distress and divide by the lane-miles in a section of road. Like PCR, this quantity can be discretized into service levels. Washington State uses this measure and divides it into intervals characterized by letter grades A-B-C-D-F (omitting E). The cutoff levels, in lane-feet of distress per lane-mile, are 500, 1000, 2500, and 5000 (WSDOT 2008).

Pavement management systems typically contain deterioration models. The deterioration of various distresses might be analyzed separately and then later combined to yield a forecast of PCR. Alternatively, the agency may compute PCR first and develop a single deterioration model for PCR. Usually these models are developed as deterministic regression equations, but Markovian models are also used by a few agencies.

4.1.7.2 End-of-Life Criteria

For life expectancy analysis, the important part of the deterioration model is the point where each condition measure reaches a minimum tolerable condition (MTC). At this point, the model assumes that pavement must either be replaced or must receive some kind of life extension action. If there are separate deterioration models for separate distresses, then the first one to reach the MTC determines the end-of-life (Figure 4-9, left side).

As discussed in Chapter 3, knowledge of the variability in age of the end-of-life is also important because it reveals how much of a population of pavement segments will reach their end-of-life within a given time frame. In a Markovian deterioration model or other probabilistic model, this variability is easily determined because the model computes the probability distribu-

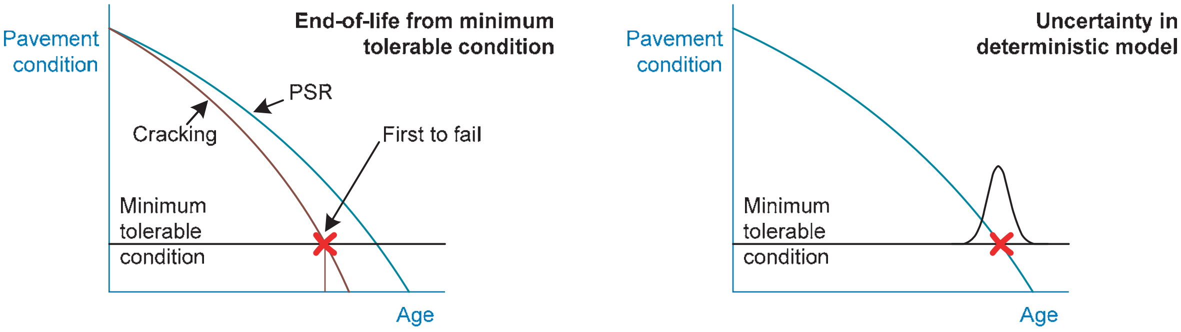


Figure 4-9. MTC and uncertainty.

tion directly. For the more common deterministic models, it is important to have a measure of regression error in the vicinity of the point where the MTC is reached (Figure 4-9, right side). Few pavement management systems provide this information.

Regardless of the deterioration model used, it is possible to work directly with historical pavement condition data to reach life expectancy in a simpler, more direct way. This starts with discretizing the range of PCR into two ranges, failed and not-failed. As a variation, the separate distresses could each be discretized in this way, with the pavement overall considered to have failed if any one of the separate measures has failed (Figure 4-10).

Frequently, in practice, pavement life is expressed as the age when the pavement is considered to need wearing surface replacement, rather than full-depth replacement. Both definitions are useful, but the results of course will differ substantially. For wearing surface life, typical end-of-life thresholds are PCR=70 (Boyer 1999, naturally depending on how PCR is defined by the agency); PSR=2.5 (CTC 2004); and IRI=170 (FHWA 2008).

Full-depth life would be indicated by levels of rutting, faulting, or structural capacity that indicate that mere surface replacement would not be sufficiently effective. Also, in practice, studies for specific transportation agencies express a longer term lifespan in terms of the total life of the original pavement plus the next three or four overlays (CTC 2004).

4.1.7.3 Life Extension Interventions

Certain routine maintenance actions, if performed consistently, can extend the life of pavements. These actions include crack sealing, surface sealing, spall patching, and drainage maintenance. Deficiencies in roughness, certain distresses, and friction can often be corrected, at least temporarily, using life extension actions. In addition, replacement of the wearing surface is often performed as a life extension activity for the full-depth pavement structure. Chapter 5 introduces some of the concepts of life extension, using deterioration and lifecycle cost models.

When estimating pavement life expectancy from historical data, it is important to know the types of routine maintenance and repair/rehabilitation actions that have been performed during each road segment's history. In many agencies, this information is missing or very difficult to use. Without this knowledge, a typical life expectancy can still be estimated, but it will not have reliable sensitivity to changes in maintenance policy, making it less useful for many common applications.

4.1.7.4 Published Life Expectancy Values

Existing literature is inconsistent about pavement life expectancy, apparently because the states differ in their construction methods, material specifications, maintenance decision-making, performance measurement, traffic characteristics, soils, and climate (CTC 2004).

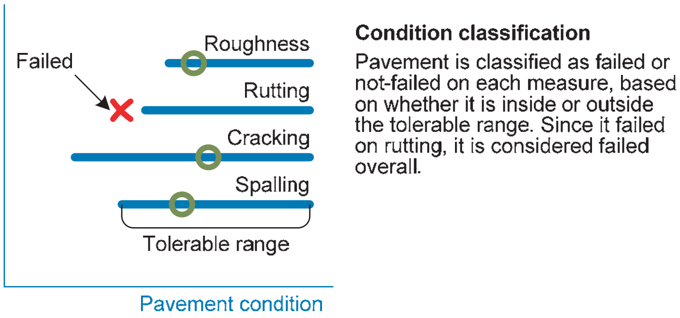


Figure 4-10. Multi-scale end-of-life criterion.

Published values of age at first overlay for asphalt concrete pavements range from 11 to 20 years; and for reinforced concrete pavements, from 20 to 34 years. The full-depth pavement life for both types of pavements is typically quoted at about 50 years; however, there is little published evidence behind these numbers.

4.1.7.5 Example Analysis

Data for analyzing pavement life and pavement treatment life were collected from the Long-Term Pavement Performance (LTPP) database and from two state DOTs. Data for new asphalt pavements were from the General Pavement Study—1 (GPS-1) of the LTPP database. Pavement sections in the GPS experiment included those with a hot-mix asphalt concrete (HMAC) surface layer with or without other HMAC layers (total HMAC layers thickness ~ 4–8 inches), placed over a granular base. The life of flexible pavement rehabilitation treatments was modeled using data from the Specific Performance Study # 5 (SPS-5) of LTPP's western region. SPS-5 has nine test sections in each participating state, and the requisite data were obtained for all the sections at all five states in the SHRP-LTPP western regions. Data included test site location, rehabilitation year, condition (in terms of IRI), climate, and treatment characteristics (e.g., thickness of new layer, level of surface preparation, and mix type).

Life of New Asphaltic Concrete Pavements. A non-parametric survival analysis (Kaplan-Meier method) was conducted to estimate the actual probability of survival of the flexible pavement sections in relation to pavement age. For purposes of illustration, it was considered that a pavement section has failed when IRI>150. Having chosen this threshold value, the estimated life represents the age at which the pavement section will need its first rehabilitation treatment. The survival curve for the GPS-1 pavement sections is shown in Figure 4-11. The figure suggests that the average life of an asphaltic pavement is approximately 25 years.

An age-based model was developed to determine the life of different rehabilitation techniques in the LTPP SPS-5 study. The number of observations is 493 and the resulting model is

$$\ln(IRI) = 0.035 + 0.049 * (AGE) - 0.12 * (LTHICK) - 0.19 * (SPREP);\ R^2 = 0.52$$

where ln(IRI) = the natural log of IRI of a treated pavement section in given year in m/km;
AGE = Time elapsed since the rehabilitation treatment, in years;
LTHICK = Indicator variable for thickness of the rehabilitation treatment (1 if 5 inches and 0 if 2 inches);
SPREP = Indicator variable for surface preparation of rehabilitation treatment (1 if intensive and 0 if minimal).

Life of Functional AC (Asphalt Concrete) Overlay Treatment. Functional AC overlay is a common rehabilitation treatment for AC pavements. The following model was developed using data from Interstates in a mid-western state in the United States. Using these data, it was determined that the best regression model for functional AC overlay performance is

$$IRI = e^{-1.37 + 2.18 \times \log(PRE\_IRI) + 0.3 \times 10^{-5} \times AGE \times TRAADT + 0.03 \times PRECIP},\ R^2 = 0.59$$

where PRE_IRI = IRI before the implementation of the treatment;
AGE = Treatment age;
TRAADT = Truck annual average daily traffic;
PRECIP = Annual average precipitation.

This makes AGE the subject of the equation and, assuming that when IRI reaches the threshold value, treatment age can be found which is equal to the treatment life, t_{SL}.

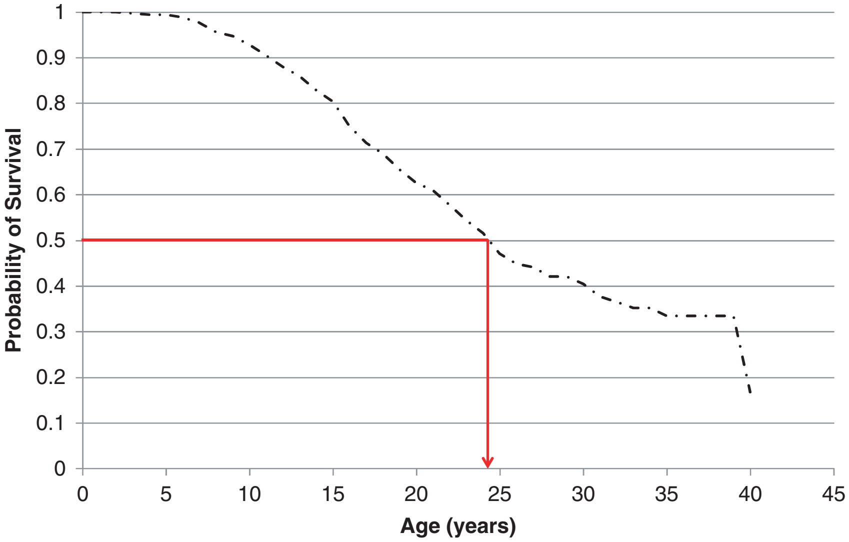


Figure 4-11. Survival curve (K-M) for rehabilitation treatments of asphaltic concrete pavements.

The functional AC overlay average life can be estimated in years. For instance, using the average values in the model, the following result was obtained:

$$t_{SL} = \frac{\ln(IRI_{Threshold}) + 1.37 - 2.18 \times Avg[\log(PRE_{IRI})] - 0.03 \times Avg(PRECIP)}{0.3 \times 10^{-5} \times Avg(TRAADT)} = 16$$

The functional AC overlay average service life was estimated at 16 years. In this illustration, the average values of the independent variables were used to estimate the average life.

Life of Resurfacing Treatment on Flexible Pavement. Data from Washington State were used to model the performance of resurfacing on existing flexible pavements. The performance indicator, IRI was used to categorize the pavements into five groups—'very good' (5) for IRI=<60, 'good' (4) for 60<IRI<94, 'fair' (3) for 94<IRI<170, 'mediocre' (2) for 170<IRI<220, and 'poor' for IRI=>220. The end-of-life was defined as the time when IRI equals 220.

A simple Markov chain model was developed, with a transition matrix as shown in Table 4-19. The model was calibrated according to the average deterioration curve, a quadratic function of the average ages in each condition state.

The resulting survival curve in Figure 4-12 suggests that the resurfacing treatment has a median life of 12 years.

Table 4-19. Markov model of pavement resurfacing.

To condition state: From condition state:	5	4	3	2	1
5	0.8176	0.1824	0	0	0
4	0	0.7408	0.2592	0	0
3	0	0	0.6230	0.3770	0
2	0	0	0	0.4361	0.5639
1	0	0	0	0	1.0000

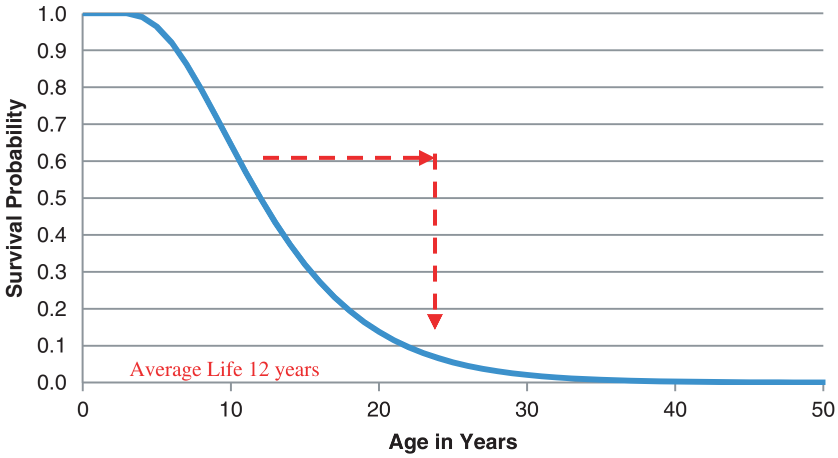


Figure 4-12. Example life expectancy estimate of pavements treated with resurfacing.

4.1.8 Bridges

Bridges consist of a collection of separate components, each with its own life expectancy. Based on site characteristics, design considerations, and market conditions, bridge designers attempt to minimize the cost of providing a given crossing for a period of 50 to 100 years. With such a long design lifespan, the end of a bridge's actual life is often shaped more by land use, economic conditions, climate change, and service standards than by material deterioration.

Over a bridge's long life, its individual components undergo traffic, weather, floods, earthquakes, collisions, movement, and fatigue, and eventually need to be replaced. At the end of a bridge's life, it may have little left of its original structure with the exception of the foundation.

Certain bridge elements are designed to take the most punishment and are intended to be replaced at relatively frequent intervals, protecting the larger and more expensive components to prolong their lives. These protective elements include expansion joints, coating systems, deck wearing surfaces, cathodic protection systems, bearings, drainage systems, pile jackets, fenders, and slope protection. The protective elements are of special concern in life expectancy analysis.

4.1.8.1 Measuring Condition and Performance

Bridges in the United States are routinely inspected, in most states on a 2-year interval, according to two sets of standards:

- The "Federal NBI Standards" were created in the early 1970s based on a Congressional mandate to provide a continuous national picture of the conditions and performance of the nation's bridges, mainly from a perspective of functionality and safety (FHWA 1995). Table 4-20 shows the definitions of the three NBI data items describing bridge condition.
- The "AASHTO Guide for Commonly-Recognized (CoRe) Structural Elements" was created in 1992 as a basis for states to describe bridge element condition at an appropriate level of detail for maintenance management (AASHTO 1997, 2002, and 2010). Table 4-21 lists the structural elements addressed by the AASHTO guide. Table 4-22 shows selected examples of condition state descriptions used by bridge inspectors to classify bridge elements.

All states are required to provide NBI data to FHWA each year, generally for all bridges and culverts over 20 feet in span that are open to the public, regardless of ownership. Forty-five states currently collect AASHTO CoRe Element data, at least for state-owned bridges. Many states gather NBI and/or AASHTO CoRe Element data for other structures where they are not

Table 4-20. NBI condition data items.

National Bridge Inventory condition data items: 58 – Deck condition 59 – Superstructure condition 60 – Substructure condition
9. EXCELLENT CONDITION
8. VERY GOOD CONDITION - no problems noted.
7. GOOD CONDITION - some minor problems.
6. SATISFACTORY CONDITION - structural elements show some minor deterioration.
5. FAIR CONDITION - all primary structural elements are sound but may have minor section loss, cracking, spalling or scour.
4. POOR CONDITION - advanced section loss, deterioration, spalling or scour.
3. SERIOUS CONDITION - loss of section, deterioration, spalling, or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
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.
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 back in light service.
0. FAILED CONDITION - out of service - beyond corrective action.

mandated, including non-bridge structures and bridges or culverts of less than 20 feet in span. Forty of the states use AASHTO's Pontis Bridge Management System to manage and use NBI and CoRe Element data (Thompson 2006).

4.1.8.2 End-of-Life Criteria

Bridges generally can qualify for federal funding for replacement if any one of the three NBI condition ratings is 4 or below. Because of funding scarcity, pre-construction activities, or related road network plans, agencies may allow a bridge to remain in condition level 4, or even condition level 3, for many years before replacing the structure. There also are often life extension opportunities at these condition levels that would improve condition for some period of time.

The NBI condition level definitions generally are not concerned with bridge maintenance and do not address the important protective elements listed above. As a result, the most relevant life expectancy issues of expansion joints, coating systems, wearing surfaces, and other shorter-lived bridge components cannot be addressed with NBI data.

Most of the agencies that collect AASHTO CoRe Element data use AASHTO's Pontis Bridge Management System to perform lifecycle cost analysis of bridge elements (Thompson 2006). In most cases, the worst-defined condition state of each element is the optimal level for element replacement. As a result, the CoRe Element language provides useful end-of-life definitions. It is convenient to define end-of-life of an element as the age when there is a 50% chance of a given unit of the element to be in its worst-defined condition state. A more sophisticated lifecycle cost analysis may indicate a different probability level.

For a bridge as a whole, the definition of end-of-life is trickier. End-of-life could be defined as the age when 50% of all the elements of the bridge (perhaps on a cost-weighted basis) are in their worst-defined condition states. To account for the many life extension opportunities, bridge end-of-life could alternatively be defined as the age when replacement has a lower lifecycle cost than any other preservation strategy. In both cases, it would be assumed that no additional preservation actions are taken in the meantime. For a bridge under a proactive maintenance

Table 4-21. AASHTO CoRe Elements.

AASHTO Commonly-Recognized (CoRe) Structural Elements

12 - Concrete Deck - Bare
13 - Concrete Deck - Unprotected w/ AC Overlay
14 - Concrete Deck - Protected w/ AC Overlay
18 - Concrete Deck - Protected w/ Thin Overlay
22 - Concrete Deck - Protected w/ Rigid Overlay
26 - Concrete Deck - Protected w/ Coated Bars
27 - Concrete Deck - Protected w/ Cathodic System
28 - Steel Deck - Open Grid
29 - Steel Deck - Concrete Filled Grid
30 - Steel Deck - Corrugated/Orthotropic/Etc.
31 - Timber Deck - Bare
32 - Timber Deck - w/ AC Overlay
38 - Concrete Slab - Bare
39 - Concrete Slab - Unprotected w/ AC Overlay
40 - Concrete Slab - Protected w/ AC Overlay
44 - Concrete Slab - Protected w/ Thin Overlay
48 - Concrete Slab - Protected w/ Rigid Overlay
52 - Concrete Slab - Protected w/ Coated Bars
53 - Concrete Slab - Protected w/ Cathodic System
54 - Timber Slab
55 - Timber Slab - w/ AC Overlay
101 - Unpainted Steel Closed Web/Box Girder
102 - Painted Steel Closed Web/Box Girder
104 - P/S Conc Closed Web/Box Girder
105 - Reinforced Concrete Closed Webs/Box Girder
106 - Unpainted Steel Open Girder/Beam
107 - Painted Steel Open Girder/Beam
109 - P/S Conc Open Girder/Beam
110 - Reinforced Conc Open Girder/Beam
111 - Timber Open Girder/Beam
112 - Unpainted Steel Stringer
113 - Painted Steel Stringer
115 - P/S Conc Stringer
116 - Reinforced Conc Stringer
117 - Timber Stringer
120 - Unpainted Steel Bottom Chord Thru Truss
121 - Painted Steel Bottom Chord Thru Truss
125 - Unpainted Steel Thru Truss (excl. bottom chord)
126 - Painted Steel Thru Truss (excl. bottom chord)
130 - Unpainted Steel Deck Truss
131 - Painted Steel Deck Truss
135 - Timber Truss/Arch
140 - Unpainted Steel Arch
141 - Painted Steel Arch
143 - P/S Conc Arch
144 - Reinforced Conc Arch
145 - Other Arch
146 - Cable - Uncoated (not embedded in concrete)
147 - Cable - Coated (not embedded in concrete)
151 - Unpainted Steel Floor Beam
152 - Painted Steel Floor Beam
154 - P/S Conc Floor Beam
155 - Reinforced Conc Floor Beam
156 - Timber Floor Beam
160 - Unpainted Steel Pin and/or Pin and Hanger Assembly
161 - Painted Steel Pin and/or Pin and Hanger Assembly
201 - Unpainted Steel Column or Pile Extension
202 - Painted Steel Column or Pile Extension
204 - P/S Conc Column or Pile Extension
205 - Reinforced Conc Column or Pile Extension
206 - Timber Column or Pile Extension
210 - Reinforced Conc Pier Wall
211 - Other Material Pier Wall
215 - Reinforced Conc Abutment
216 - Timber Abutment
217 - Other Material Abutment
220 - Reinforced Conc Submerged Pile Cap/Footing
225 - Unpainted Steel Submerged Pile
226 - P/S Conc Submerged Pile
227 - Reinforced Conc Submerged Pile
228 - Timber Submerged Pile
230 - Unpainted Steel Cap
231 - Painted Steel Cap
233 - P/S Conc Cap
234 - Reinforced Conc Cap
235 - Timber Cap
240 - Unpainted Steel Culvert
241 - Reinforced Concrete Culvert
242 - Timber Culvert
243 - Other Culvert
300 - Strip Seal Expansion Joint
301 - Pourable Joint Seal
302 - Compression Joint Seal
303 - Assembly Joint/Seal (modular)
304 - Open Expansion Joint
310 - Elastomeric Bearing
311 - Moveable Bearing (roller, sliding, etc.)
312 - Enclosed/Concealed Bearing
313 - Fixed Bearing
314 - Pot Bearing
315 - Disk Bearing
320 - P/S Concrete Approach Slab w/ or w-o/AC Only
321 - Reinforced Conc Approach Slab w/ or w/o AC Only
330 - Metal Bridge Railing - Uncoated
331 - Reinforced Conc Bridge Railing
332 - Timber Bridge Railing
333 - Other Bridge Railing
334 - Metal Bridge Railing - Coated
356 - Steel Fatigue
357 - Pack Rust
358 - Deck Cracking
359 - Soffit of Concrete Deck or Slab
360 - Settlement
361 - Scour
362 - Traffic Impact
363 - Section Loss

program, it is conceivable that asset life could be extended far beyond its design life, until fatigue, functional requirements, or natural or man-made hazards finally bring its life to an end.

4.1.8.3 Life Extension Interventions

Bridge life extension activities can occur at any point in a structure's life. Bridge washing and concrete sealing can occur even on new bridges. Some of the most cost-effective life extension options occur with bridges in mid-life, when opportunities arise to keep protective systems such as expansion joints, paint, wearing surfaces, and bearings in good repair. During the life of

Table 4-22. Example AASHTO CoRe Element condition states.

13 - Concrete Deck - Unprotected w/ AC Overlay	107 - Painted Steel Open Girder/Beam
1. The surfacing on the deck has no patched areas and there are no potholes in the surfacing.	1. There is no evidence of active corrosion, and the paint system is sound and functioning as intended to protect the metal surface.
2. Patched areas and/or potholes or impending potholes exist. Their combined area is 10% or less of the total deck area.	2. There is little or no active corrosion. Surface or freckled rust has formed or is forming. The paint system may be chalking, peeling, curling, or showing other early evidence of paint system distress, but there is no exposure of metal.
3. Patched areas and/or potholes or impending potholes exist. Their combined area is more than 10% but 25% or less of the total deck area.	3. Surface or freckled rust is prevalent. There may be exposed metal, but there is no active corrosion which is causing loss of section.
4. Patched areas and/or potholes or impending potholes exist. Their combined area is more than 25% but less than 50% of the total deck area.	4. Corrosion may be present but any section loss due to active corrosion does not yet warrant structural analysis of either the element or the bridge.
5. Patched areas and/or potholes or impending potholes exist. Their combined area is 50% or more of the total deck area.	5. Corrosion has caused section loss and is sufficient to warrant structural analysis to ascertain the impact on the ultimate strength and/or serviceability of either the element or the bridge.

106 - Unpainted Steel Open Girder/Beam	111 - Timber Open Girder/Beam
1. There is little or no corrosion of the unpainted steel. The weathering steel is coated uniformly and remains in excellent condition. Oxide film is tightly adhered.	1. Investigation indicates no decay. There may be superficial cracks, splits, and checks having no effect on strength or serviceability.
2. Surface rust or surface pitting has formed or is forming on the unpainted steel. The weathering steel has not corroded beyond design limits. Weathering steel color is yellow orange to light brown. Oxide film has a dusty to granular texture.	2. Decay, insect/marine borer infestation, abrasion, splitting, cracking, checking, or crushing may exist but none is sufficiently advanced to affect strength or serviceability of the element.
3. Steel has measurable section loss due to corrosion but does not warrant structural analysis. Weathering steel is dark brown or black. Oxide film is flaking.	3. Decay, insect/marine borer infestation, abrasion, splitting, cracking, or crushing has produced loss of strength or deflection of the element but not of a sufficient magnitude to affect the serviceability of the bridge.
4. Corrosion is advanced. Oxide film has a laminar texture with thin sheets of rust. Section loss is sufficient to warrant structural analysis to ascertain the impact on the ultimate strength and/or serviceability of either the element or the bridge.	4. Deterioration is advanced. Decay, insect/marine borer infestation, abrasion, splits, cracks, or crushing has produced loss of strength or deflection that affects the serviceability of the bridge.

109 - P/S Conc Open Girder/Beam	110 - Reinforced Conc Open Girder/Beam
1. The element shows little or no deterioration. There may be discoloration, efflorescence, and/or superficial cracking but without effect on strength and/or serviceability.	1. The element shows little or no deterioration. There may be discoloration, efflorescence, and/or superficial cracking but without effect on strength and/or serviceability.
2. Minor cracks and spalls may be present, and there may be exposed reinforcing with no evidence of corrosion. There is no exposure of the prestress system.	2. Minor cracks and spalls may be present, but there is no exposed reinforcing or surface evidence of rebar corrosion.
3. Some delamination and/or spalls may be present. There may be minor exposure but no deterioration of the prestress system. Corrosion of non-prestressed reinforcement may be present, but loss of section is incidental and does not significantly affect the strength and/or serviceability of either the element or the bridge.	3. Some delamination and/or spalls may be present and some reinforcing may be exposed. Corrosion of rebar may be present, but loss of section is incidental and does not significantly affect the strength and/or serviceability of either the element or the bridge.
4. Delamination, spalls, and corrosion of non-prestressed reinforcement are prevalent. There may also be exposure and deterioration of the prestress system (manifested by loss of bond, broken strands or wire, failed anchorages, etc). There is sufficient concern to warrant an analysis to ascertain the impact on the strength and/or serviceability of either the element or the bridge.	4. Deterioration is advanced. Corrosion of reinforcement and/or loss of concrete section are sufficient to warrant analysis to ascertain the impact on the strength and/or serviceability of either the element or the bridge.

(continued on next page)

Table 4-22. (Continued).

300 - Strip Seal Expansion Joint	311 - Moveable Bearing (roller, sliding, etc.)
1. The element shows minimal deterioration. There is no leakage at any point along the joint. Gland is secure and has no defects. Debris in joint is not causing any problems. The adjacent deck and/or header are sound.	1. The element shows little or no deterioration. The paint system, if present, is sound and functioning as intended to protect the metal. The bearing has minimal debris and corrosion. Vertical and horizontal alignments are within limits. Bearing support member is sound. Any lubrication system is functioning properly.
2. Signs of seepage along the joint may be present. The gland may be punctured, ripped, or partially pulled out of the extrusion. Significant debris is in all or part of the joint. Minor spalls in the deck and/or header may be present, adjacent to the joint.	2. The paint system, if present, may show moderate to heavy corrosion with some pitting but still functions as intended. The assemblies may have moved enough to cause minor cracking in the supporting concrete. Debris buildup is affecting bearing movement. Bearing alignment is still tolerable.
3. Signs or observance of leakage along the joint may be present. The gland may have failed from abrasion or tearing. The gland has pulled out of the extrusion. Major spalls may be present in the deck and/or header adjacent to the joint.	3. There is advanced corrosion with section loss. There may be loss of section of the supporting member sufficient to warrant supplemental supports or load restrictions. Bearing alignment may be beyond tolerable limits. Shear keys may have failed. The lubrication system, if any, may have failed.

a bridge, its deck may be entirely replaced two or more times. It is often possible to replace the entire superstructure. Concrete rehabilitation activities and slope protection on the substructure can keep it in service for a very long time. Bridge management systems, with their thorough deterioration models and lifecycle costing capabilities, are necessary for finding the best life extension opportunities.

4.1.8.4 Published Life Expectancy Values

There are no authoritative published sources of life expectancy estimates for bridges, other than those concerned with design life. However, many states have now collected 12 years' or more of CoRe Element data, enough to develop reliable life expectancy estimates. The Pontis Bridge Management System has a built-in process, described in Chapter 5, to generate Markovian transition probabilities from inspection data (Cambridge 2003). Life expectancy estimates can be readily generated from Markovian transition probability matrices using the methods described later in this chapter.

4.1.8.5 Example Analysis

A 2010 study for Florida DOT (Thompson and Sobanjo 2010) used the one-step method described in Chapter 5 to estimate Markovian transition probabilities for groups of bridge and non-bridge elements in the Florida inventory. The bridge elements use the CoRe Element condition rating system described above. Table 4-23 presents the resulting life expectancy estimates for all of the bridge and non-bridge elements.

From these estimates, it can be seen that cross-sectional methods such as Markovian models are capable of providing life expectancy estimates for very long-lived facilities. In Florida's inventory, the concrete elements in particular enter the worst condition state, where replacement may be warranted, very infrequently. This fact leads to life expectancies of hundreds of years in some cases.

Given that Florida has more than 19,000 structures and biennial inspections covering 14 years of history, the sample sizes used in these estimates range from 547 to 47,725 inspection pairs. Concrete elements have the largest sample sizes because they are the most common material used in Florida's inventory.

Florida's results, in a relatively benign environment where deicing chemicals are not used, are not necessarily indicative of other states. An FHWA study of Pontis deterioration models across the

Table 4-23. Florida bridge and non-bridge element life expectancies (Thompson and Sobanjo 2010).

Element type	Life (yrs)
A1- Concrete deck	146
A2- Concrete slab	98
A3- Prestressed concrete slab	174
A4- Steel deck	37
A5- Timber deck/slab	41
A6- Approach slabs	83
B1- Strip Seal expansion joint	67
B2- Pourable joint seal	23
B3- Compression joint seal	21
B4- Assembly joint/seal	34
B5- Open expansion joint	58
B6- Other expansion joint	92
C1- Uncoated metal rail	84
C2- Coated metal rail	45
C3- Reinforced concrete railing	163
C4- Timber railing	26
C5- Other railing	62
D1- Unpainted steel super/substructure	46
D2- Painted girder/floorbeam/cable/p&h	99
D3- Painted steel stringer	323
D4- Painted steel truss bottom	51
D5- Painted steel truss/arch top	189
D6- Prestressed concrete superstr	335
D7- Reinforced concrete superstructure	80
D8- Timber superstructure	92
E1- Elastomeric bearings	393
E2- Metal bearings	72
F1- Painted steel substructure	32
F2- Prestressed column/pile/cap	142
F3- Reinforced concrete column/pile	200
F5- Reinforced concrete abutment	656
F6- Reinforced concrete cap	428
F7- Pile cap/footing	116
F8- Timber substructure	58
G1- Reinforced concrete culverts	208
G2- Metal and other culverts	91
H1- Channel	66
I1- Pile jacket w/o cathodic protection	63
I2- Pile jacket with cathodic protection	150
I3- Fender/dolphin/bulkhead/seawall	60
I4- Reinforced conc slope protection	99
I5- Timber slope protection	260
I6- Other (incl asphalt) slope protection	71
I7- Drainage system	17
I7- Drainage system (coated)	17
J1- Uncoated metal wall	95
J2- Reinforced concrete wall	158
J3- Timber wall	61
J4- Other (incl masonry) wall	62
J5- Mechanically stabilized earth wall	119
K1- Sign structures/hi-mast light poles	51
K1- Sign str/hi-mast light poles (coated)	99
L1- Moveable bridge mechanical	73
L2- Moveable bridge brakes	25
L3- Moveable bridge motors	34
L4- Moveable bridge hydraulic power	48
L5- Moveable bridge pipe and conduit	37
L6- Moveable bridge structure	38
L7- Moveable bridge locks	31
L8- Moveable bridge live load items	32
L9- Moveable bridge cw/trunion/track	124
M1- Moveable bridge electronics	70
M2- Moveable bridge submarine cable	22
M3- Moveable bridge control console	31
M4- Moveable bridge navigational lights	23
M5- Moveable bridge operator facilities	59
M6- Moveable bridge misc equipment	13
M7- Moveable bridge barriers/gates	37
M8- Moveable bridge traffic signals	41

nation (Thompson 2007) found that a state with a very severe winter environment, such as Maine, can have bridge element life expectancies that are only half those of Florida. In warm very dry regions, such as southern California, life expectancy may be more than twice as long as in Florida.

4.1.9 Other Asset Types

Although not within the scope of this guide, there are several other highway asset types for which a life expectancy analysis is appropriate and for which the methods described in this guide could be used:

- Paved and unpaved ditches and swales
- Storm detention ponds
- Dams
- Fences
- Landscaping

- Retaining walls
- Sound barriers
- Guiderails and impact attenuators
- Rest area facilities
- Tunnels
- Weigh stations
- Maintenance facilities
- Highway agency vehicles and equipment

4.1.10 Summary Estimates

From the literature, wide ranges in asset life were found, with estimates varying by material/design type, end-of-life threshold applied, climatic conditions, and levels of applied maintenance. Typical values by asset class were found to be overall bridge life equal to 50–60 years, bridge deck life equal to 25–45 years, culvert life equal to 30–50 years, traffic sign life equal to 10–20 years, pavement markings life equal to 1–5 years, traffic signal life equal to 15–20 years, and roadway lighting life equal to 25–30 years.

4.2 Developing Life Expectancy Models

When not from published sources, the method of developing life expectancy models depends very much on the kind of data available. The most significant considerations are as follows:

- Availability of data on past replacement actions;
- Availability of data on past life extension actions;
- Availability of relevant inventory, condition, and performance data on existing assets;
- Availability of relevant inventory, condition, and performance data on assets that no longer exist because they were replaced;
- Availability of a time series of past observations of condition and performance, preferably evenly spaced in time;
- Consistency of data collection definitions and processes over time;
- Quality of the existing models and judgment, including research literature that can be helpful in selecting an appropriate model form; and
- Degree to which the available data are representative of the population whose life expectancy is desired.

The final point is especially challenging because construction methods, materials, and utilization change over time. Even if the agency has quality data about its historical infrastructure, newer facilities may have different performance characteristics. Thus, it may be necessary to make adjustments based on laboratory data or judgment.

Another important consideration that interacts with data availability is the type of policy sensitivity desired. A model based on actual replacement activities may correspond with a commonly understood concept of life expectancy, but the data set may contain assets replaced for various reasons that might not be representative of future assets or future policies under consideration (Figure 4-13).

One way to respond to the diversity of most real-life data sets is to try to separate the population into groups, according to the reasons for replacement and the types of actions that may have been taken. These sorts of historical data are often very difficult to find and interpret successfully.

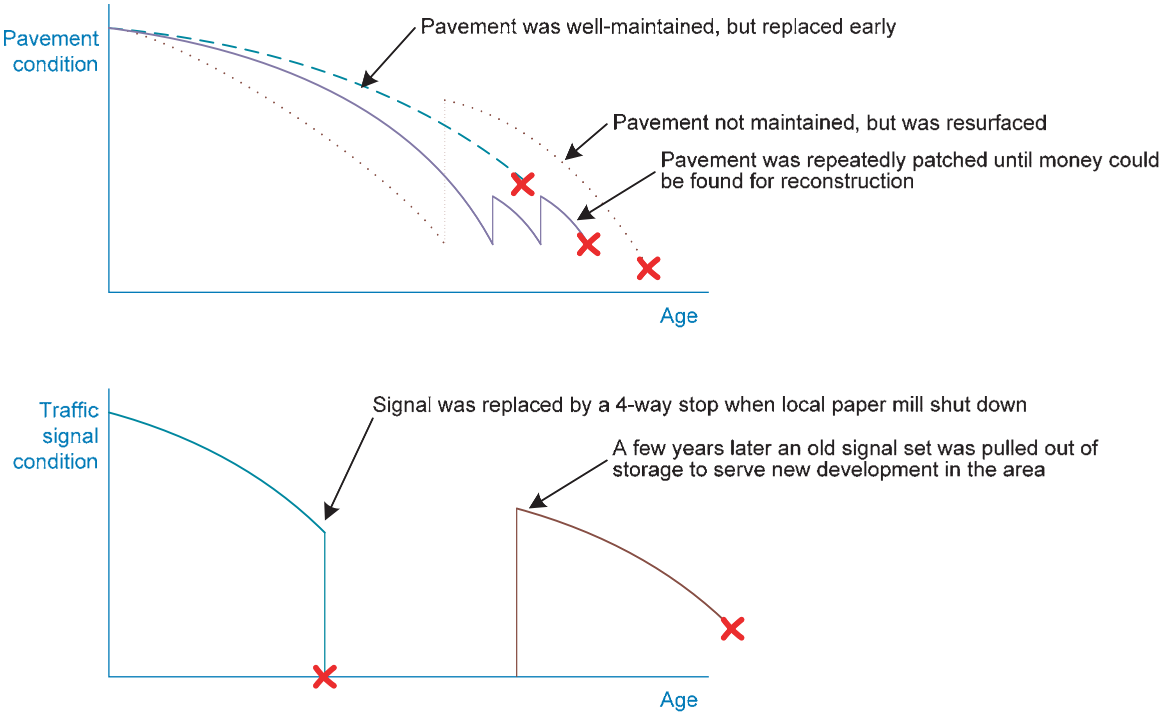


Figure 4-13. Difficulties in using historical replacement data.

Moreover, if the goal is to quantify asset longevity in the absence of extenuating circumstances, then it is often more useful to work with condition data directly and quantify the length of the deterioration curve, regardless of whether or not the asset was replaced exactly at the end of the curve. Historical condition data are often easier to find, especially for assets that are still in service and have not yet been replaced. Most of the examples given earlier in this chapter are based on this perspective.

As Chapter 5 will show, many of the useful applications of life expectancy analysis involve life-cycle costing and a comparison of design and life extension alternatives. For these applications, it is important to try to separate the effect of simple deterioration, deterioration under preventive maintenance, and the beneficial effects of specific actions of interest. In practice, it is often easier and more useful to model these effects separately and combine them later to simulate possible future policies.

4.2.1 Ordinary Regression of Age At Replacement

If the goal is a direct model of age at replacement, one approach is to develop a regression model with age at replacement as the dependent variable. Possible sources of data are as follows:

- A contract management system or maintenance management system which provides the age or year of construction of the asset that was taken out of service.
- Records of asset demolition, combined with archived inventory records for the demolished assets. There would need to be a way of associating records in the two databases; for example, a common identifier or description.
- Archived inventory records that directly indicate the date the asset was taken out of service.
- If new assets carry the same identification number or location tag as the assets they replace, then a time series of condition might show a sudden improvement that pinpoints the time of replacement.

The simplest possible model would be a model which does not have any explanatory variables (Table 4-24). In other words, simply make a list of all the replacement ages of the assets and compute the average.

In this example, the table on the left-hand side contains a list of culverts, along with the age at which each culvert was replaced. The table on the right shows the average replacement age for each district and the standard deviation. The ability to calculate separate averages for each district is useful if this reflects different conditions of climate, topography, or soils, all of which could affect life expectancy.

In a real analysis, it would be necessary to have a longer list of culverts, at least 30 in each district, in order to obtain statistically reliable results. If the number of data points available is substantially larger, it would be possible to divide up the model more finely if desired, to make it sensitive to more variables that might affect culvert life expectancy. For example, separate averages could be computed for different soil types. In that case, each separate category would need at least 30 data points.

The standard deviation is useful for describing how certain the estimate of life expectancy may be, when applied to a future set of culverts. That the average replacement age in District 1 was 50.75 does not mean that all future culverts will fail at the exact age of 50 years and 9 months. Some will fail sooner, some later; and the standard deviation is an estimate of how much sooner or later.

Table 4-24 shows the formulas for computing standard deviation. If the data set is a complete list of all the culverts replaced, then the formula for population standard deviation should be used. If the list is a random sample, use the sample standard deviation formula. When developing an application in a programming language such as Visual Basic or C#, it will be necessary to write computer code for these formulas.

Table 4-24, like all the examples in this guide, can be found in a Microsoft Excel spreadsheet file available on line. A table and a graph showing the probability of replacement for each possible age of a culvert also can be found in the spreadsheet for this example. This is computed directly from the average and standard deviation, under the assumption that the

Table 4-24. Average age at replacement.

List of culverts with age at replacement				
District name	Culvert identifier	Replace-ment age	Deviation from avg	Square of deviation
District	**CulvertID**	**ReplAge**	**Deviation**	**SqDev**
D1	195451	55	4.25	18.0625
D1	185701	52	1.25	1.5625
D1	137132	47	-3.75	14.0625
D1	194845	49	-1.75	3.0625
D2	268014	42	-1.50	2.2500
D2	205563	47	3.50	12.2500
D2	261619	41	-2.50	6.2500
D2	275579	48	4.50	20.2500
D2	226692	39	-4.50	20.2500
D2	278272	44	0.50	0.2500
D3	352904	46	5.40	29.1600
D3	372275	41	0.40	0.1600
D3	326486	37	-3.60	12.9600
D3	306439	39	-1.60	2.5600
D3	314958	40	-0.60	0.3600

Average and standard deviation of age at replacement				
District name	Number of culverts	Average age	Population StDev (1)	Sample StDev (2)
District	**Count**	**AvgAge**	**PopStDev**	**SamStDev**
D1	4	50.75	3.03	3.50
D2	6	43.50	3.20	3.51
D3	5	40.60	3.01	3.36

Average age at replacement
a is culvert age, N is number of culverts

$$\bar{a} = \frac{1}{N}\sum_{i=1}^{N} a_i$$

Population standard deviation
(use if list is whole population)

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(a_i - \bar{a}\right)^2}$$

Sample standard deviation
(use if list is a random sample)
s is an estimate of σ

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(a_i - \bar{a}\right)^2}$$

variation in replacement age is shaped like the normal distribution. Figure 4-14 shows the graph for District D1.

In order to compute the probability of replacement at any given age, the formula for a normal distribution was used. This formula is

$$Prob = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{(a-\bar{a})^2}{2\sigma^2}\right)$$

where *a* is the age (horizontal axis) and σ is the standard deviation.

This formula can be used as an estimate of the fraction of culverts that will need to be replaced each year (labeled "This year" on the graph). To determine how many culverts will need to be replaced in the next 10 years, the most accurate approach is to use the cumulative normal distribution, which computes the total area under the normal distribution up to a given time. Although this distribution does not have an easy formula, there is an approximation that is just as good for practical purposes.

$$CumProb = \frac{1}{2}\left(\frac{z}{|z|}\sqrt{1-exp\left(-z^2 \times \frac{\frac{4}{\pi}+kz^2}{1+kz^2}\right)}+1\right) \qquad z = \frac{(a-\bar{a})}{\sqrt{2}\sigma} \qquad k = 0.140012$$

The value of *k* is a mathematical constant and is the same for any age or type of asset. The fraction just before the radical, *z,* divided by the absolute value of *z,* serves only to change the sign of the square-root term so the formula works equally well before or after the average replacement age (Note: If this analysis is performed in a Microsoft Excel spreadsheet, the function NORMDIST can be used in place of this large formula for CumProb, and gives a more precise result. An example worksheet accompanying this report compares the two methods.)

If a family of culverts, all installed at the same time, are now 40 years old, the number likely to be replaced in the next 10 years can be computed from

$$Prob = CumProb(50) - CumProb(40)$$

In other words, compute the cumulative probability before age 50, and subtract the cumulative probability before age 40 (the current age), to arrive at the estimate, which in this case is about 40%. Even though the average age at replacement is 50.75 years, and it is now only year 40, about 40% of the culverts probably will need to be replaced within the next 10 years, in this example. This is just another example of why it's important to measure uncertainty in life expectancy analysis.

It is useful to develop a model that has causal factors or that at least distinguishes different asset characteristics. The feasibility of this will depend, of course, on whether the distinguishing characteristics of the assets are available in the data. Two ways of doing this are

- Partitioning. The data set can be divided into groups according to one or more classification variables, as was done in Table 4-24 for districts. Then, simple averaging or a regression model can be developed separately for each group.
- Linear or non-linear regression. This process develops a mathematical model to compute life expectancy as a function of one or more explanatory variables (Table 4-25). Linear regression models can be developed using regression as described in the following paragraphs. Certain types of non-linear models can also be developed in this way. For more complex non-linear models, software can be used to perform maximum likelihood estimation.

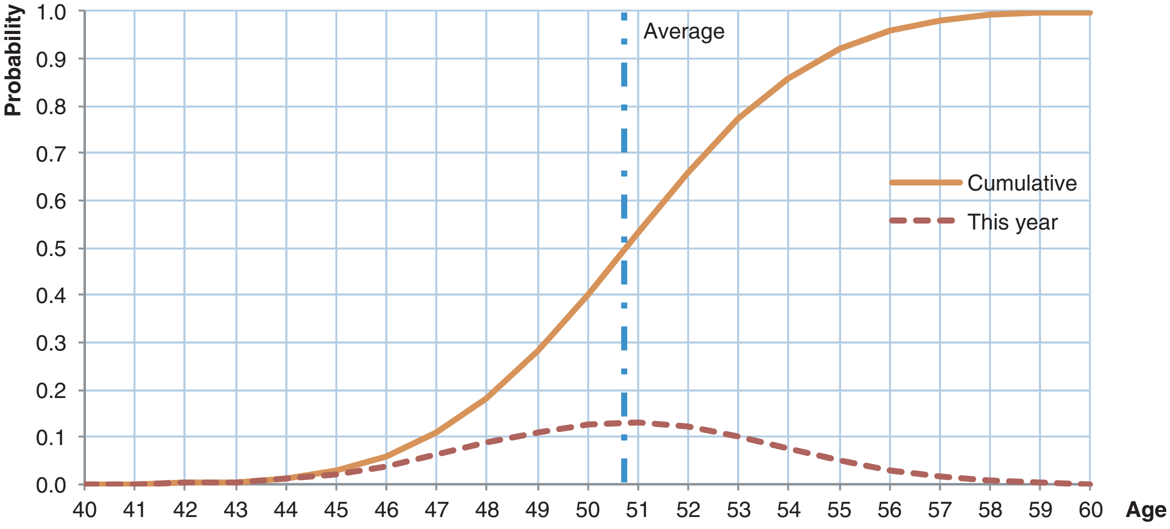


Figure 4-14. Graph of replacement probability, from the data in Table 4-24.

Table 4-25. Regression of age at replacement.

List of culverts with age at replacement

District name	Culvert identifier	Replace-ment age	1 if D1	1 if D2	Barrel length	Predict age	Devi-ation	Sq of Devn
District	**CulvertID**	**ReplAge**	**Dist1**	**Dist2**	**Length**	**Pred**	**Devn**	**SqDev**
D1	195451	55	1	0	20	52.50	2.50	6.27
D1	185701	52	1	0	36	51.02	0.98	0.95
D1	137132	47	1	0	40	50.68	-3.68	13.56
D1	194845	49	1	0	62	48.80	0.20	0.04
D2	268014	42	0	1	48	45.65	-3.65	13.29
D2	205563	47	0	1	59	44.62	2.38	5.68
D2	261619	41	0	1	86	42.30	-1.30	1.68
D2	275579	48	0	1	77	43.03	4.97	24.69
D2	226692	39	0	1	100	40.99	-1.99	3.95
D2	278272	44	0	1	62	44.42	-0.42	0.18
D3	352904	46	0	0	48	44.80	1.20	1.44
D3	372275	41	0	0	106	39.65	1.35	1.82
D3	326486	37	0	0	86	41.37	-4.37	19.11
D3	306439	39	0	0	120	38.44	0.56	0.32
D3	314958	40	0	0	116	38.74	1.26	1.58

Average and standard deviation of repl age

District name	Number of culverts	Average age	Population StDev
District	**Count**	**AvgAge**	**PopStDev**
D1	4	50.75	2.28
D2	6	43.50	2.87
D3	5	40.60	2.20

Regression results

R-squared	0.75		
Variable	Coeffi-cient	Standard error	t-Statistic
Intercept	49.02	3.77	13.01
Dist1	5.22	2.85	1.83
Dist2	0.85	1.97	0.43
Length	-0.09	0.04	-2.38

Table 4-25 uses the same culverts as in Table 4-24. The only difference in the data set is that barrel length (in feet) has been included as an additional explanatory variable. The analyst believes that longer culverts are more likely to be damaged by debris washing through them and less likely to be thoroughly cleaned by the agency's routine annual flushing, hence a shorter life expectancy. Regression variables should not be added unless the analyst has a credible intuitive reason why such variables should be significant.

As in the previous example, the analyst believes "district" should be significant because it reflects different conditions of climate, topography, or soils. Because district is a categorical variable, it cannot be used directly in a regression model. A way around this is to create "dummy variables" to represent the separate districts. So the variable Dist1 is 1 if the culvert is in District 1, and 0 otherwise. Dist2, similarly, is 1 if in District 2, 0 otherwise. There is no Dist3 variable. This is because Dist3 would be mutually correlated with Dist1 and Dist2. In fact, it can easily be computed from Dist1 and Dist2. In a regression model, all of the variables must be independent of each other. Some software packages check for such situations; others do not.

In order to use Microsoft Excel's linear regression capability, it is necessary to make sure it is installed. On the Data ribbon in Microsoft Excel 2007, check for "Data Analysis" in the "Analysis" section on the right side of the Data ribbon (Figure 4-15). If it is not present, do the following:

1. Click the Microsoft Office button (in the upper left corner of Figure 4-15) and then click "Excel Options."
2. Click the "Add-Ins" tab on the left side of the window (Figure 4-16).
3. In the pick list labeled "Manage" in the bottom center of the Add-Ins window, choose "Excel Add-Ins," then click "Go . . ."
4. Another dialog box will appear (Figure 4-17), which should list "Analysis ToolPack" as one of its choices. Check the box next to it. If "Analysis ToolPack" does not appear in the list, you may need to click "Browse . . ." and search for it. At this point you may also want to check "Solver Add-in" since this will be used in later examples in this guide. Then click OK.
5. If you are prompted to install the Analysis ToolPack, click "Yes" and proceed with installing it, according to the program's instructions.
6. At this point, the Analysis ToolPack should appear on the Data ribbon as in Figure 4-15.

With the Analysis ToolPack ready to use, click the "Data Analysis" button to start the regression process. A menu of analysis types will be shown, where you should choose "Regression" and click "OK" as in Figure 4-18.

When the example in the accompanying Microsoft Excel file was created, its linear regression options were set up as in Figure 4-19. The "Input Y Range" should be the data set column containing the variable that you are trying to estimate, in this case the age at replacement (ReplAge). Include the column label in the range. "Input X Range" is a group of columns containing the explanatory variables for the model. It includes the columns Dist1, Dist2, and Length. "Output Range" should point to the upper left cell in an area of the worksheet that does not contain any other information because the regression procedure will overwrite these cells with the results.

Click "OK" to run the regression. The results are placed in the worksheet and, from there, can be moved or reformatted as desired. The most important results are reported in the lower right table in Table 4-25. An R-squared value of 0.75 is quite good; even 0.5 is often acceptable when the data set has few good explanatory variables. The t-Statistic column shows the performance of the individual explanatory variables. If the absolute value is at least 1.5 or 2.0, then the variable is considered to be a strong contributor to the model. A smaller t-Statistic might be acceptable, however, if the variable contributes to the intuitive sensibility of the model or if it is necessary for using the model. Because a great many factors can influence deterioration, and only a few of these are ever measured, it is best to keep the number of variables minimal and just use the strongest and most necessary ones.

If the R-squared value or t-Statistics are small, and there are no explanatory variables that improve them, this means that the regression method is not adding much value compared with the simple average computed in the previous example.

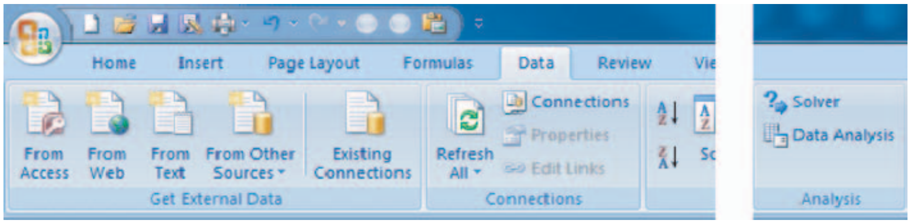
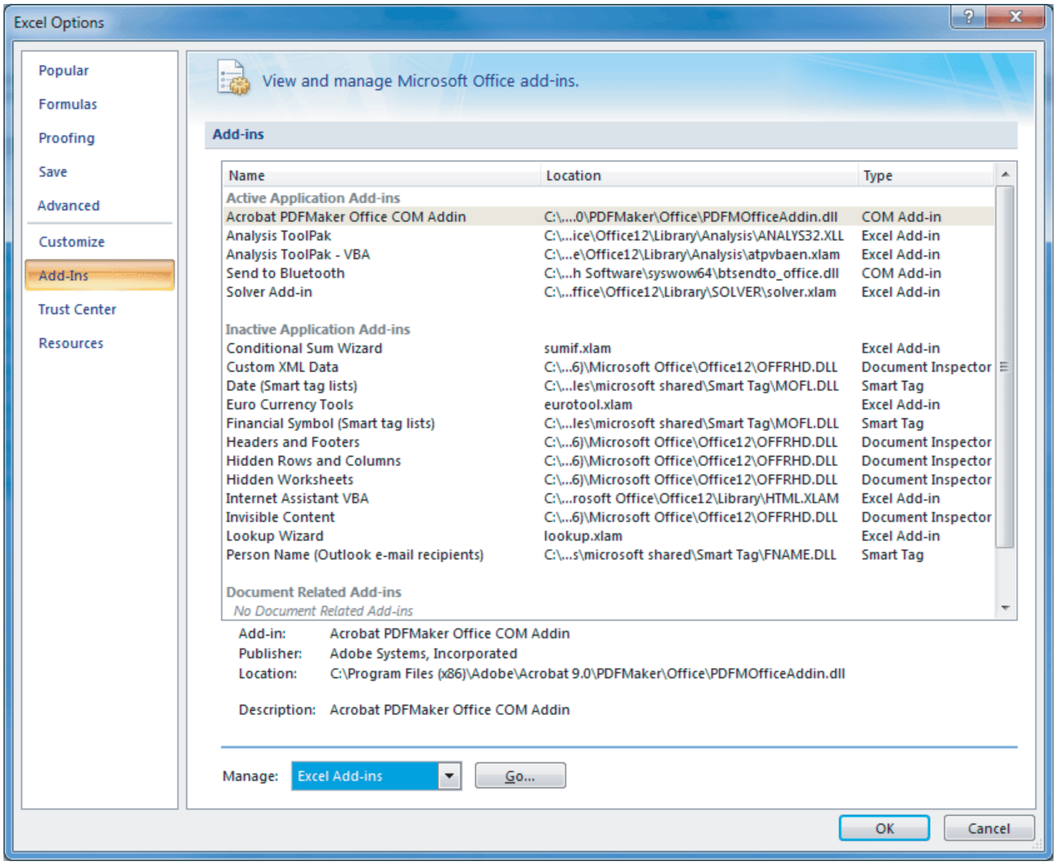


Figure 4-15. The Data ribbon showing "Data Analysis" button.



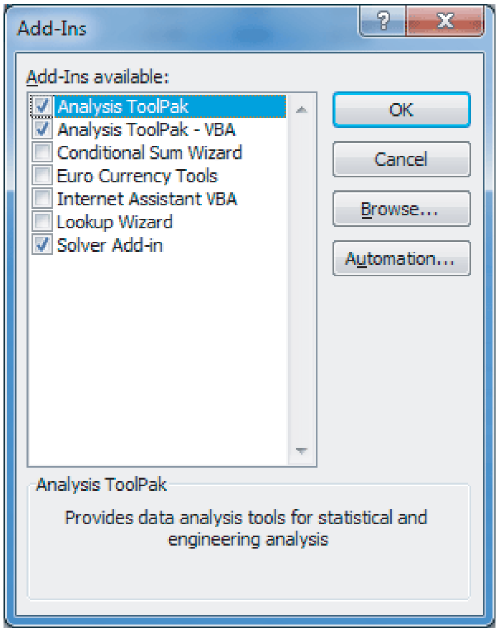
Name	Location	Type
Active Application Add-ins		
Acrobat PDFMaker Office COM Addin	C:\....0\PDFMaker\Office\PDFMOfficeAddin.dll	COM Add-in
Analysis ToolPak	C:\...ice\Office12\Library\Analysis\ANALYS32.XLL	Excel Add-in
Analysis ToolPak - VBA	C:\...e\Office12\Library\Analysis\atpvbaen.xlam	Excel Add-in
Send to Bluetooth	C:\...h Software\syswow64\btsendto_office.dll	COM Add-in
Solver Add-in	C:\...ffice\Office12\Library\SOLVER\solver.xlam	Excel Add-in
Inactive Application Add-ins		
Conditional Sum Wizard	sumif.xlam	Excel Add-in
Custom XML Data	C:\...6)\Microsoft Office\Office12\OFFRHD.DLL	Document Inspector
Date (Smart tag lists)	C:\...les\microsoft shared\Smart Tag\MOFL.DLL	Smart Tag
Euro Currency Tools	eurotool.xlam	Excel Add-in
Financial Symbol (Smart tag lists)	C:\...les\microsoft shared\Smart Tag\MOFL.DLL	Smart Tag
Headers and Footers	C:\...6)\Microsoft Office\Office12\OFFRHD.DLL	Document Inspector
Hidden Rows and Columns	C:\...6)\Microsoft Office\Office12\OFFRHD.DLL	Document Inspector
Hidden Worksheets	C:\...6)\Microsoft Office\Office12\OFFRHD.DLL	Document Inspector
Internet Assistant VBA	C:\...rosoft Office\Office12\Library\HTML.XLAM	Excel Add-in
Invisible Content	C:\...6)\Microsoft Office\Office12\OFFRHD.DLL	Document Inspector
Lookup Wizard	lookup.xlam	Excel Add-in
Person Name (Outlook e-mail recipients)	C:\...s\microsoft shared\Smart Tag\FNAME.DLL	Smart Tag
Document Related Add-ins		
No Document Related Add-ins		

Add-in: Acrobat PDFMaker Office COM Addin
Publisher: Adobe Systems, Incorporated
Location: C:\Program Files (x86)\Adobe\Acrobat 9.0\PDFMaker\Office\PDFMOfficeAddin.dll

Description: Acrobat PDFMaker Office COM Addin

Manage: Excel Add-ins [Go...]

Figure 4-16. Manage Office add-ins.



Add-Ins available:
☑ Analysis ToolPak
☑ Analysis ToolPak - VBA
☐ Conditional Sum Wizard
☐ Euro Currency Tools
☐ Internet Assistant VBA
☐ Lookup Wizard
☑ Solver Add-in

Analysis ToolPak
Provides data analysis tools for statistical and engineering analysis

Figure 4-17. Add-ins dialog.

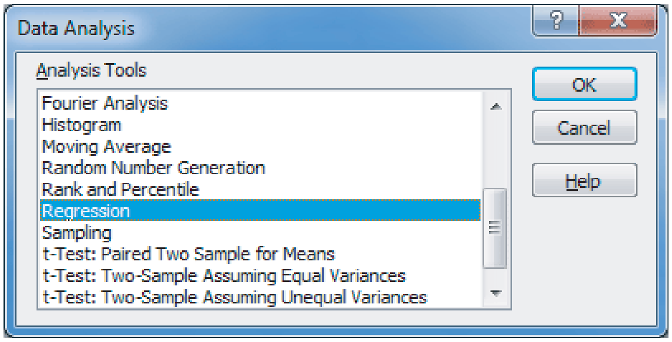
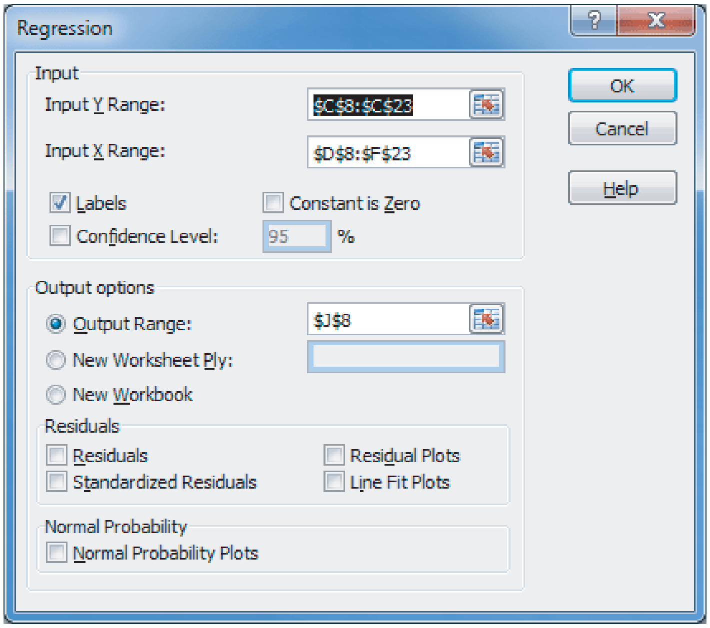


Figure 4-18. Choosing Regression.



Input Y Range: $C$8:$C$23

Input X Range: $D$8:$F$23

☑ Labels

☐ Constant is Zero

☐ Confidence Level: 95 %

● Output Range: $J$8

○ New Worksheet Ply:

○ New Workbook

☐ Residuals

☐ Standardized Residuals

☐ Residual Plots

☐ Line Fit Plots

☐ Normal Probability Plots

Figure 4-19. Launching the regression process.

Based on the results reported in this example, the predicted life expectancy of a culvert is computed from the following equation:

$$\acute{a} = 49.02 + 5.22 \times Dist1 + 0.85 \times Dist2 - .09 \times Length$$

Consistent with the input data, the age is in years and the length is in feet. The results are consistent with the previous example, in that District 1 and District 2 both have longer life expectancies than District 3. The effect of length is as the analyst expected. The negative coefficient means that longer lengths have shorter lifespans.

Using this regression formula, the predicted replacement age estimates are placed in Table 4-25 at the beginning of this example (column Pred), for comparison with the actual values (column ReplAge). Standard deviation can be computed from this information in exactly the same way as for simple averaging, using the predicted value instead of the average. It can be seen that the new estimates are generally closer than the estimates obtained from simple averaging. The upper-right table shows smaller standard deviations, which means that the addition of barrel length as an explanatory variable improved the precision of the model.

For the purposes of programming, the method of simple averaging in the preceding example is still the most straightforward way of determining the needed level of investment in each district within any given time frame. The addition of the length variable improves the quality of forecasts for individual culverts, but it does not change the amount of variability within each district, assuming each district has about the same variability of culvert barrel lengths. What the regression model does provide is the accurate computation of priority and schedule for replacement of each individual culvert and a better indication of which culverts (namely, the longest ones) will be needing replacement within the 10-year program.

In research studies that have developed regression models of replacement age, sample sizes of at least 100 have usually been sufficient for models having up to five or six explanatory variables. There is rarely any need to have more explanatory variables than six. This of course does not mean that every model with at least 100 data points is good. If the explanatory variables are weak or if they are moderately correlated with each other (rather than completely uncorrelated, which is desired), then larger data sets are likely to be needed. It is often useful to partition a regression model; for example, making a separate model for each district or functional class. In this case, each of the sub-models needs to have a sufficient sample size.

One of the pitfalls of using regression models for life expectancy is the possibility of bias due to an effect called "censoring." The regression model is developed from past replacements and gives an average age at replacement. This is not necessarily the same thing as life expectancy, however, because some of the assets that should be in the data set have unknown replacement dates in the future. These replacement dates are hidden, or "censored" from the analyst. Figure 4-20 shows this.

The left side of the figure depicts a list of assets having various procurement and disposal dates. At the time of the analysis, many of these assets are still in service so they have unknown disposal dates in the future. On the right side, a typical normal probability distribution of replacement age is shown. If the full population is used for analysis, then among the assets procured more recently than the typical asset lifespan, some will have failed and some will still be in service. A data set that contains all of the historical replacements from this population will have too many early replacements and not enough late replacements. As a result, the right side of the normal probability distribution is cut off. In this situation, the average computed from this data set will be biased toward a shorter life expectancy than the true value.

One possible solution to this problem is to limit the data set to older assets, those that were procured so long ago that they are almost certain to have been replaced. This time interval can be determined by starting from the published life expectancy estimates and adding a safety allowance; or by using a time interval that is longer than all, or nearly all (for example, 95%), of the life spans in the data set. Only assets put in service before the start of this time interval would be used in the analysis.

Of course, this approach has problems which might make it difficult to follow. Older data usually are of lower quality so the precision or confidence level of the results may be reduced.

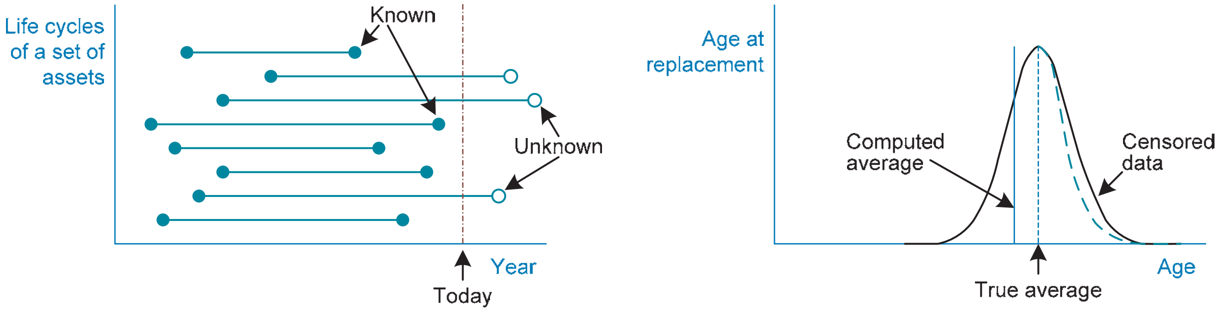


Figure 4-20. Censoring of time series data.

Also, certain assets are so long-lived that it may be impossible to exclude enough of them. For example, the typical life span of a bridge currently in service may be 50 years, and the analyst might judge that 70 years gives enough of a safety margin to include 95% of all bridge lifespans. The agency might have relatively few records concerning bridges built so long ago though, and the oldest databases of bridge condition in the United States go back only about 40 years. As a result, correcting for one bias might cause other biases.

Because of these issues, the ordinary regression approach might not work well for long-lived assets where the censoring problem arises. Fortunately, there are better alternatives, which are discussed in the following sections.

4.2.2 Markov Model

In the previous section, one of the simplest possible approaches to computing life expectancy was to compute the average age of all demolished assets in a data set. Unfortunately, data issues may make this method impractical or inaccurate in many cases. There is another very simple method, the Markov model. In exchange for accepting a few simplifying assumptions, the Markov model avoids a great many of the data quality and censoring problems that plague regression models.

The Markov model adopts a totally different perspective from regression models. The first important characteristic of a Markov model is that it defines end-of-life in terms of condition, rather than action. The full range of possible conditions of an asset is divided into a small number of condition states. Many of the examples given in earlier sections of this guide used condition rating schemes based on condition states. Two prominent examples are the Washington State Maintenance Accountability Process (WSDOT 2008) and the AASHTO CoRe Structural Elements Process (AASHTO 1997, 2002, and 2010).

To use a condition state rating scheme in a Markov model of life expectancy, first define "failed" as the worst of the defined condition states. This does not necessarily mean that a structure literally fell down or even that its condition is interfering with traffic. It may mean that an asset in the worst condition state is a strong candidate for replacement. It might also be a strong candidate for a life extension action such as rehabilitation.

There can be any number of additional condition states besides "failed." In the simplest case, there might be just one additional state, "not-failed." The WSDOT process consistently uses five states, and the AASHTO CoRe Elements process uses four. If condition data are gathered using visual inspection techniques, it may be difficult to discern more than three or four states reliably. The ability to discern more condition states can produce a more precise and accurate model if the data can be gathered accurately (Table 4-26).

Table 4-26. Condition states for a Markov model of life expectancy.

107 - Painted Steel Open Girder/Beam	
1. There is no evidence of active corrosion, and the paint system is sound and functioning as intended to protect the metal surface.	
2. There is little or no active corrosion. Surface or freckled rust has formed or is forming. The paint system may be chalking, peeling, curling, or showing other early evidence of paint system distress, but there is no exposure of metal.	
3. Surface or freckled rust is prevalent. There may be exposed metal but there is no active corrosion which is causing loss of section.	
4. Corrosion may be present but any section loss due to active corrosion does not yet warrant structural analysis of either the element or the bridge.	← **"Almost failed" state**
5. Corrosion has caused section loss and is sufficient to warrant structural analysis to ascertain the impact on the ultimate strength and/or serviceability of either the element or the bridge.	← **"Failed" state**

When the condition of an asset is determined, the entire asset might be classified in one of the condition states. Alternatively, the quantity of the asset (e.g., feet of culvert) might be divided among the states. For example, an inspector might assess a 100-foot long steel beam and decide that 10 feet are in state 5, 20 feet in state 4, and the remainder in state 1. Any population of assets (e.g., 100,000 feet of steel girder on 150 different bridges) can also be described by the percent in each condition state.

Building on this discrete condition state concept, the Markov model makes a few additional assumptions:

- Condition is determined on a regular interval, such as once a year.
- Over any single interval, a unit of the asset either remains in the same condition state or jumps to one of the other states. No in-between states are observed.
- The probability of jumping from any one state to any other state is a constant.

The first two of these assumptions usually are dictated by routine data collection practices so they are easy to accept. The third one, often called the "memoryless assumption," requires more thought however.

Because of the memoryless assumption, a Markov deterioration model always looks like Table 4-27. If a piece of steel girder is in condition state 1 this year, then next year there is (for this example) a 95.3% chance it will still be in state 1. If there are 100,000 feet of steel girder in state 1 now, then next year 95,300 feet will still be in state 1, 4,600 feet will be in state 2, 100 feet in state 3, and none in states 4 or 5. Each row of the table sums to 100%.

The numbers in the body of Table 4-27 are called "transition probabilities," because they are the probabilities of making each possible state transition. The matrix describes what happens in one year, but it is easy to compute the transition probabilities for any number of years into the future by multiplying the matrix by itself that many times (Table 4-28).

So the condition of the inventory of assets deteriorates steadily over time and obviously varies with age. However, the transition probabilities themselves are constant: they don't change as the asset gets older, and are not affected by anything that may have happened to the facility in the past. The only variation that is allowed is an improvement in condition if an action is taken this year. This is what is meant by the "memoryless assumption."

Because future predictions of condition are made by using matrix multiplication, it is possible to start with an asset that is entirely in state 1, and repeatedly multiply by the transition probability matrix until the fraction in the failed state finally reaches 50%. Doing that would simulate the years of the asset's life until half of them have failed, thus giving an estimate of the typical life expectancy of the asset, which is flagged in Table 4-28 as 40 years.

Table 4-27. Example Markov deterioration model.

		Probability of each condition state one year later (%)				
		1	2	3	4	5
Condition state now	1	95.3	4.6	0.1	0	0
	2	0	93.2	3.9	1.9	1.0
	3	0	0	89.4	7.3	3.3
	4	0	0	0	82.8	17.2
	5	0	0	0	0	100

Table 4-28. Markov model prediction.

Markov transition probability matrix

State	State probability in one year				
Today	1	2	3	4	5
1	95.3	4.6	0.1	0.0	0.0
2	0	93.2	3.9	1.9	1.0
3	0	0	89.4	7.3	3.3
4	0	0	0	82.8	17.2
5	0	0	0	0	100

Probability of state k next year: $y_k = \sum_j x_j p_{jk}$ for all k

j is the condition state this year and x is the fraction in state j
p is the transition probability from j to k

Future condition forecasts

	Percent by condition state					
Year	1	2	3	4	5	
0	100	0	0	0.0	0.0	
1	95.3	4.6	0.1	0.0	0.0	
2	90.8	8.7	0.4	0.1	0.0	
3	86.6	12.3	0.8	0.3	0.2	
4	82.5	15.4	1.2	0.5	0.4	
5	78.6	18.2	1.8	0.8	0.6	
6	74.9	20.5	2.4	1.1	1.0	
7	71.4	22.6	3.0	1.5	1.5	
8	68.0	24.3	3.6	1.9	2.1	
9	64.8	25.8	4.3	2.3	2.8	
10	61.8	27.0	4.9	2.7	3.6	
11	58.9	28.0	5.5	3.1	4.5	
12	56.1	28.8	6.1	3.5	5.5	
13	53.5	29.5	6.6	3.9	6.6	
14	51.0	29.9	7.1	4.3	7.7	
15	48.6	30.2	7.6	4.6	9.0	
16	46.3	30.4	8.0	5.0	10.4	
17	44.1	30.5	8.4	5.3	11.8	
18	42.0	30.4	8.7	5.5	13.3	
19	40.1	30.3	9.0	5.8	14.8	
20	38.2	30.1	9.3	6.0	16.4	
21	36.4	29.8	9.5	6.3	18.1	
22	34.7	29.4	9.7	6.4	19.7	
23	33.0	29.0	9.9	6.6	21.5	
24	31.5	28.6	10.0	6.7	23.2	
25	30.0	28.1	10.1	6.8	25.0	
25	30.0	28.1	10.1	6.8	25.0	
26	28.6	27.6	10.1	6.9	26.8	
27	27.3	27.0	10.2	7.0	28.6	
28	26.0	26.4	10.2	7.1	30.4	
29	24.8	25.8	10.1	7.1	32.2	
30	23.6	25.2	10.1	7.1	34.0	
31	22.5	24.6	10.0	7.1	35.8	
32	21.4	23.9	9.9	7.1	37.6	
33	20.4	23.3	9.8	7.0	39.4	
34	19.5	22.6	9.7	7.0	41.2	
35	18.5	22.0	9.6	6.9	42.9	
36	17.7	21.4	9.5	6.9	44.7	
37	16.8	20.7	9.3	6.8	46.4	
38	16.1	20.1	9.1	6.7	48.0	
39	15.3	19.5	9.0	6.6	49.7	
40	14.6	18.8	8.8	6.5	51.3	<< Median life expectancy
41	13.9	18.2	8.6	6.4	52.9	
42	13.2	17.6	8.4	6.2	54.5	
43	12.6	17.0	8.2	6.1	56.0	
44	12.0	16.5	8.0	6.0	57.5	
45	11.5	15.9	7.8	5.9	58.9	
46	10.9	15.3	7.6	5.7	60.4	
47	10.4	14.8	7.4	5.6	61.8	
48	9.9	14.3	7.2	5.5	63.1	
49	9.5	13.8	7.0	5.3	64.4	
50	9.0	13.3	6.8	5.2	65.7	

The methods for developing Markov deterioration models are described in Chapter 5. But even without going through the process of deterioration modeling, there is a simpler, quick-and-easy way of estimating life expectancy using the ideas behind the Markov model. It proceeds through these steps (Table 4-29):

1. Starting from a list of past condition state inspections, collapse the states into just two: failed and not-failed. For example, if traffic signals are rated on a four-state scale, and a particular intersection was inspected in 2007 with 25% of signal heads in state 1, 25% in state 2, 25% in state 3, and 25% in state 4 (the "failed" state), then count this inspection as 75% not-failed and 25% failed.
2. Group the inspections of each facility into pairs, each with an interval of one year. (Other intervals are also possible, as described in the final step below.) So each pair describes the condition before and after a one-year period.
3. Remove from the pairs list any pairs that are believed to have received life extension work. This determination might be based on maintenance records if available or might be based on

improvement in condition (i.e., where the percent not-failed increased from before to after). These signal installations probably received some kind of life extension or replacement activity.

4. Over the entire list of inspection pairs, compute the average percent in failed and not-failed for the before case, and again for the after case. This is a measure of condition for the inventory as a whole, comparing before and after any typical one-year period when no action was taken.
5. Compute the probability of remaining in the non-failed state as the non-failed percent after, divided by the non-failed percent before. Call this the "same-state" probability. The deterioration probability then is one minus the same-state probability.
6. Based on the matrix algebra described above, the median life expectancy is readily computed as:

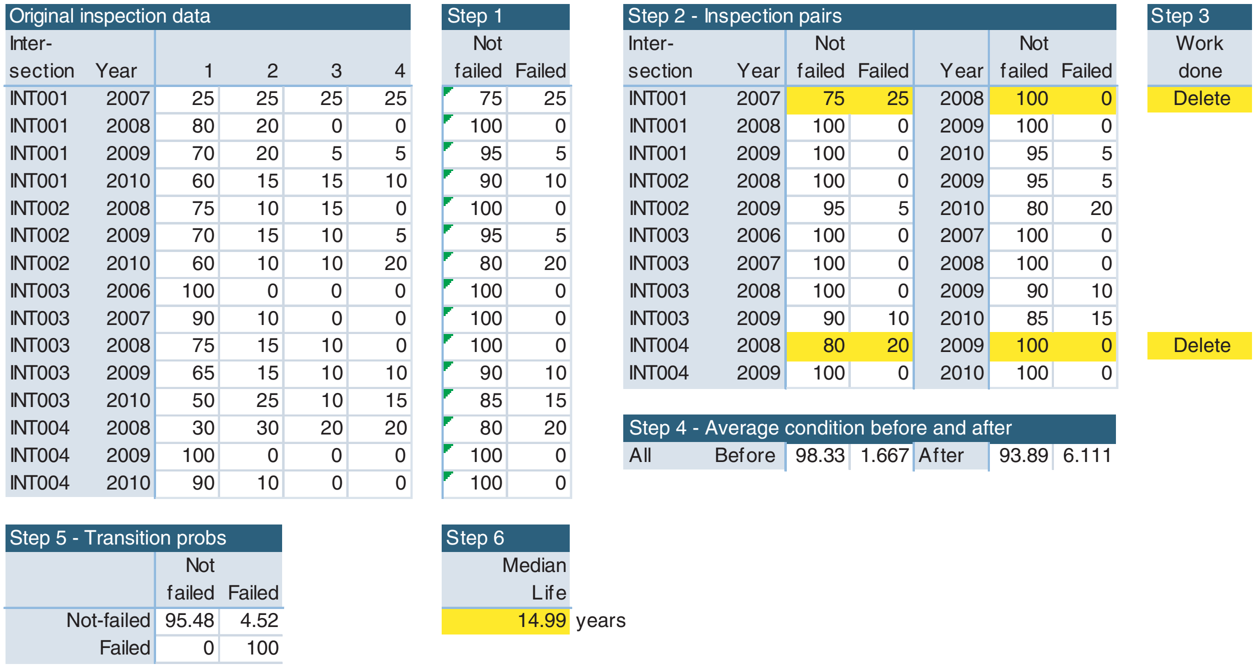
$$t = \frac{\log(0.5)}{\log(p_{jj})}$$

where t is the median life expectancy and pjj is the same-state probability.

7. If the 50% threshold of the failed state is too high (for example, if planning a blanket replacement project for an asset type where failure creates a hazard to the public), simply replace 0.5 with the desired threshold in this formula, such as 5%. If the inspection interval is something other than 1 year (it must be of some uniform length), then t is expressed in terms of intervals and can be converted to years. For example, if the inspection interval is 2 years, then multiply t by 2 in order to express life expectancy in years.

This procedure is just a special case of the "one-step method" for the Markov deterioration models described in Chapter 5. Even though the method is quite rough, it may be appropriate for data sets that also are very rough, especially when the condition is only described in terms of pass/fail in the first place. The method is especially valuable because it makes efficient use of small data sets in order to develop separate models for subsets of the inventory, such as wire-mounted versus pole-mounted signal heads or components from different manufacturers or with different features. Thus, it is a very practical and useful solution for many types of assets.

Table 4-29. Quick-and-dirty Markov life expectancy.



Original inspection data						Step 1	
Inter-section	Year	1	2	3	4	Not failed	Failed
INT001	2007	25	25	25	25	75	25
INT001	2008	80	20	0	0	100	0
INT001	2009	70	20	5	5	95	5
INT001	2010	60	15	15	10	90	10
INT002	2008	75	10	15	0	100	0
INT002	2009	70	15	10	5	95	5
INT002	2010	60	10	10	20	80	20
INT003	2006	100	0	0	0	100	0
INT003	2007	90	10	0	0	100	0
INT003	2008	75	15	10	0	100	0
INT003	2009	65	15	10	10	90	10
INT003	2010	50	25	10	15	85	15
INT004	2008	30	30	20	20	80	20
INT004	2009	100	0	0	0	100	0
INT004	2010	90	10	0	0	100	0

Step 2 - Inspection pairs							Step 3
Inter-section	Year	Not failed	Failed	Year	Not failed	Failed	Work done
INT001	2007	75	25	2008	100	0	Delete
INT001	2008	100	0	2009	100	0	
INT001	2009	100	0	2010	95	5	
INT002	2008	100	0	2009	95	5	
INT002	2009	95	5	2010	80	20	
INT003	2006	100	0	2007	100	0	
INT003	2007	100	0	2008	100	0	
INT003	2008	100	0	2009	90	10	
INT003	2009	90	10	2010	85	15	
INT004	2008	80	20	2009	100	0	Delete
INT004	2009	100	0	2010	100	0	

Step 4 - Average condition before and after						
All	Before	98.33	1.667	After	93.89	6.111

Step 5 - Transition probs		
	Not failed	Failed
Not-failed	95.48	4.52
Failed	0	100

Step 6	
Median Life	
14.99	years

4.2.3 Weibull Survival Probability Model

The Markov model described in the preceding section is simple, but for certain applications it may be too simple. The memoryless assumption is often viewed as a weakness because it implies that the rate of deterioration does not increase with age.

Consider a galvanized steel guardrail, for example. As long as the metal coating on the rail is solid, the rail will deteriorate slowly. However, if the coating starts to break down due to chemical attack (e.g., from deicing salts), contact with moving objects, and age, it begins to expose the underlying steel. The steel deteriorates at a faster rate as the effectiveness of the coating declines.

This problem can be addressed with a more detailed visual inspection, such as what is common on bridge rails; but an agency may not want to make a data collection investment of that magnitude. Perhaps the agency rates guardrail condition using a video log so technicians are only able to discern pass/fail condition states when viewing the video in the office.

Fortunately, it is not too difficult to add age dependency to the Markov model, making it into what is called a "Weibull survival probability" model. Weibull models are useful as deterioration models, an application discussed in Chapter 5, but they are also useful for the simpler purpose of life expectancy estimation. The Weibull curve has the following functional form:

$$y_{1g} = \exp\left(-1.0 \times (g/\alpha)^{\beta}\right)$$

where y_{1g} is the probability of the not-failed state at age g, if no intervening maintenance action is taken between year 0 and year g; β is the shaping parameter, which determines the initial slowing effect on deterioration (e.g., when the galvanized coating is performing well); and α is the scaling parameter, calculated as

$$\alpha = \frac{t}{(\ln 2)^{1/\beta}}$$

where t is the median life expectancy from the Markov model as calculated in the preceding section.

Figure 4-21 shows the form of the Weibull curve, for four different values of the shaping parameter β, with $t = 20$. A shaping parameter of 1 is mathematically equivalent to a Markov model (also known as an exponential distribution), where the transition probability does not

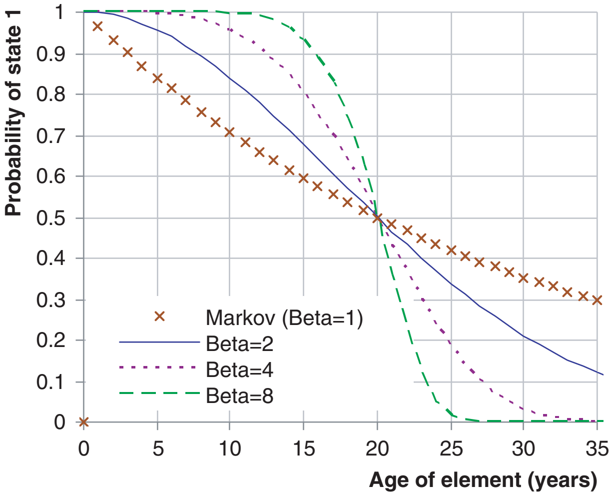


Figure 4-21. Examples of the Weibull survival probability model.

vary with age. Higher shaping parameters slow the initial rate of deterioration, which then accelerates as the facility gets older. Note that all the curves intersect in 20 years at a probability of 0.5, since the median transition time is the same in all cases.

It is important to note that the Weibull model does not change the Markov median life expectancy and is not necessary if median life expectancy is the only result desired from the analysis. Where the Weibull model helps is in the calculation of uncertainty in life expectancy. As the shaping parameter increases, the range of uncertainty narrows. In Figure 4-21, the Markov model, after 10 years, has a 70% survival probability; in other words, 30% of the inventory will need to be replaced during a 10-year program period. However, if the shaping parameter is 8, the survival probability after 10 years is nearly 100%, with little or no replacement funding needed.

The shaping parameter can be determined using a statistical procedure called "maximum likelihood estimation," which is a structured trial-and-error procedure to experiment with different values of beta until the best fit to the data is found. (Note: The trial-and-error can be orchestrated by Microsoft Excel's Solver module or can be done manually by inputting the possible values in a spreadsheet.)

To develop the Weibull model, perform all of the steps described in the preceding section for the Markov model, with the following enhancements:

- When forming pairs in Step 2, keep track of the age of the asset at the time of the second inspection in each pair.
- When filtering pairs in Step 3, keep track of the pairs that are removed.

After completing the calculation of Markov model life expectancy, remove from the data set not only the pairs where work may have been done, but also remove all subsequent pairs for those assets. Because the Weibull model is a time-series analysis, it is necessary to have inspection data for ages at least up to the Markov median life expectancy. The analysis works best on assets where it is unusual to perform life extension work before the median life expectancy is reached.

Table 4-30 shows a list of road segments with data on their traffic signs. In the example agency, signs are inspected on a pass/fail basis every 2 years. The pass/fail criterion is a level-of-service standard based on retroreflectivity and damage. Each segment of road has a group of signs, which is characterized by the fraction satisfying the level-of-service standard. This lends itself to a relatively low-cost drive-by visual process of rating sign condition.

It is desired to estimate a model of the fraction of signs that pass the standards as a function of age. For this model, the only required data for each segment of road are the age (assuming all signs on the segment were installed at the same time) and the fraction that passed.

The procedure for estimating the model is called "maximum likelihood estimation." This is an iterative process that starts with an initial educated guess and then uses a systematic trial-and-error process to improve on the guess. The guesses are directed by the objective of maximizing the likelihood that the estimated parameters are the correct ones.

On the right-hand side of the spreadsheet, the median life expectancy and shaping parameter are initially provided by the analyst as educated guesses, perhaps based on published life expectancy estimates. For the example, it would make sense to use initial values of 10 years for life expectancy, 2.0 as the shaping parameter, and 0.01 as the standard deviation. In most cases the initial values would not affect the results, as long as they are reasonable. The prediction equation is

$$y_g = \exp\left(-1 \times (g/\alpha)^{\beta}\right) \qquad \alpha = \frac{T}{(\ln 2)^{1/\beta}}$$

where y_g is the fraction predicted to pass at age g; α is the scaling parameter; β is the shaping parameter; and T is the median life expectancy.

Table 4-30. Weibull survival probability model for signs.

List of biennial traffic sign inspections

Road segment	Year of insp	Age of signs	Actual fraction passing	Predict fraction passing	Markov fraction passing	Square of deviation act-pred	Square of deviation act-mean	Log likelihood
Segment	**Year**	**Age**	**Pass**	**Predicted**	**Markovq**	**DevPred**	**DevMean**	**LogLike**
RS00001	1994	0	1.00	1.000	1.000	0.0000	0.0976	1.584
RS00001	1996	2	1.00	0.966	0.869	0.0012	0.0976	1.496
RS00001	1998	4	0.99	0.880	0.755	0.0121	0.0914	0.682
RS00001	2000	6	0.95	0.761	0.657	0.0356	0.0688	-1.071
RS00001	2002	8	0.89	0.627	0.571	0.0692	0.0410	-3.577
RS00001	2004	10	0.62	0.492	0.496	0.0163	0.0046	0.369
RS00001	2006	12	0.43	0.369	0.431	0.0037	0.0664	1.309
RS00001	2008	14	0.31	0.265	0.375	0.0020	0.1426	1.431
RS00001	2010	16	0.19	0.182	0.326	0.0001	0.2476	1.579
RS00002	1998	0	1.00	1.000	1.000	0.0000	0.0976	1.584
RS00002	2000	2	0.96	0.966	0.869	0.0000	0.0742	1.581
RS00002	2002	4	0.88	0.880	0.755	0.0000	0.0370	1.584
RS00002	2004	6	0.73	0.761	0.657	0.0010	0.0018	1.510
RS00002	2006	8	0.64	0.627	0.571	0.0002	0.0023	1.571
RS00002	2008	10	0.51	0.492	0.496	0.0003	0.0315	1.561
RS00002	2010	12	0.42	0.369	0.431	0.0026	0.0716	1.392
RS00003	1996	0	1.00	1.000	1.000	0.0000	0.0976	1.584
RS00003	1998	2	0.97	0.966	0.869	0.0000	0.0797	1.582
RS00003	2000	4	0.91	0.880	0.755	0.0009	0.0495	1.517
RS00003	2002	6	0.71	0.761	0.657	0.0026	0.0005	1.387
RS00003	2004	8	0.58	0.627	0.571	0.0022	0.0116	1.419
RS00003	2006	10	0.41	0.492	0.496	0.0068	0.0771	1.077
RS00003	2008	12	0.34	0.369	0.431	0.0009	0.1208	1.520
RS00003	2010	14	0.21	0.265	0.375	0.0030	0.2281	1.360
RS00004	1998	0	1.00	1.000	1.000	0.0000	0.0976	1.584
RS00004	2000	2	0.95	0.966	0.869	0.0002	0.0688	1.565
RS00004	2002	4	0.87	0.880	0.755	0.0001	0.0333	1.576
RS00004	2004	6	0.73	0.761	0.657	0.0010	0.0018	1.510
RS00004	2006	8	0.54	0.627	0.571	0.0076	0.0218	1.019
RS00004	2008	10	0.44	0.492	0.496	0.0027	0.0613	1.379
RS00004	2010	12	0.31	0.369	0.431	0.0035	0.1426	1.322
RS00005	1996	0	1.00	1.000	1.000	0.0000	0.0976	1.584
RS00005	1998	2	1.00	0.966	0.869	0.0012	0.0976	1.496
RS00005	2000	4	0.91	0.880	0.755	0.0009	0.0495	1.517
RS00005	2002	6	0.83	0.761	0.657	0.0047	0.0203	1.232
RS00005	2004	8	0.71	0.627	0.571	0.0069	0.0005	1.070
RS00005	2006	10	0.51	0.492	0.496	0.0003	0.0315	1.561
RS00005	2008	12	0.46	0.369	0.431	0.0082	0.0518	0.970
RS00005	2010	14	0.33	0.265	0.375	0.0043	0.1279	1.266
RS00006	1998	0	1.00	1.000	1.000	0.0000	0.0976	1.584
RS00006	2000	2	0.95	0.966	0.869	0.0002	0.0688	1.565
RS00006	2002	4	0.79	0.880	0.755	0.0081	0.0105	0.979
RS00006	2004	6	0.61	0.761	0.657	0.0229	0.0060	-0.125
RS00006	2006	8	0.43	0.627	0.571	0.0388	0.0664	-1.311
RS00006	2008	10	0.32	0.492	0.496	0.0297	0.1351	-0.634
RS00006	2010	12	0.29	0.369	0.431	0.0063	0.1581	1.115

Coeff	Value
Median years	9.88
Shaping param	1.87
Std deviation	0.0819
Sum LogLike	49.852
Scaling param	12.025
Markov scaling	14.259
Mean passing	0.6876
SSE	0.3083
SST	3.2848
R-squared	0.9061

The value of *T* can be determined using the Markov model described in the previous example. For this example, however, it is determined using maximum likelihood estimation at the same time as the shaping parameter. The Weibull model gives the same results as the Markov model if the shaping parameter is 1.0. This is shown in the Markov column of the spreadsheet.

To assist with further computations, the spreadsheet has a column showing the square of the deviation between actual and predicted, calculated as

$$SqDevPred = (Pass - Predicted)^2$$

Also shown is the square of the deviation between actual and mean, calculated as

$$SqDevMean = (Pass - MeanPassing)^2$$

The maximum likelihood procedure tries to find values of median life expectancy and shaping parameter that maximize the value of a "log likelihood function," which is just a measure of how likely the parameters are to be the correct ones that explain the observed data. The likelihood function is a formula chosen to converge quickly on the best solution, in order to make the procedure as fast as possible. This formula is

$$LogLikelihood = -0.5 \times \ln(2\pi) - 0.5 \times \ln(\sigma^2) - 0.5 \times SqDevPred/(\sigma^2)$$

The standard deviation σ is determined iteratively by the estimation procedure, based on the choices for life expectancy and shaping parameter. The sum of log likelihood over all the data points is shown in the upper-right table of the example, just below the parameters to be estimated.

As a more familiar measure of goodness-of-fit, the example spreadsheet also computes R-squared, using the formula

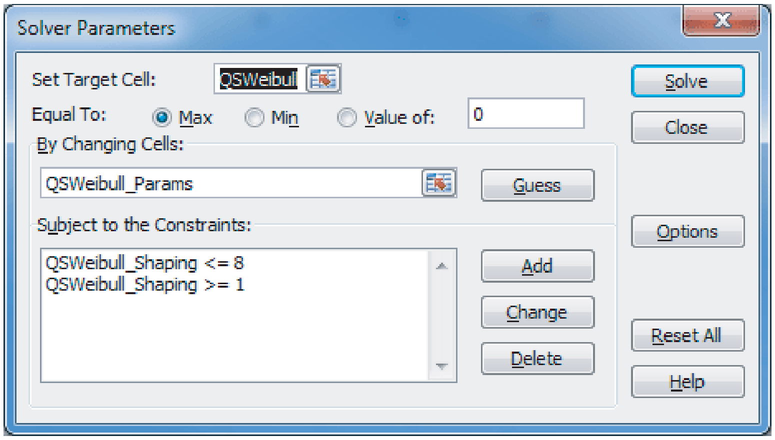
$$R^2 = 1 - \frac{\sum_i SqDevPred}{\sum_i SqDevMean}$$

This has the same interpretation as in linear regression. It is an estimate of how much of the variability in the dependent variable (fraction that passed) is explained by the model. It can be used to compare different versions of the model, to see which one has the best fit to the data.

Microsoft Excel's Solver module is used in order to drive the trial-and-error process of finding the best values of life expectancy and shaping parameter. The Solver module appears on the Data ribbon in Microsoft Excel 2007. See the linear regression example above for instructions on how to ensure that the Solver is installed. Click the Solver button, and complete the Solver dialog box as shown in Figure 4-22.

The target cell is the cell containing the sum of the log likelihood function. This is the quantity to be maximized. The "By Changing Cells" range is the range containing the cells whose values are to be estimated. It consists of three cells in this example: Median years (life expectancy), Shaping parameter, and Standard deviation. The constraints set a maximum and minimum value on the shaping parameter, which are included just to prevent the model from finding nonsensical values of the shaping parameter. Click the "Solve" button to perform the estimation procedure. Microsoft Excel will present the results and ask whether to keep them. The example above shows the final values of the parameters.

The main difference between the Weibull survival probability model and the Markov model is the ability to include age as an explanatory variable. Figure 4-23 shows the effect.



Set Target Cell: QSWeibull

Equal To: ● Max ○ Min ○ Value of: 0

By Changing Cells: QSWeibull_Params

Subject to the Constraints:

QSWeibull_Shaping <= 8
QSWeibull_Shaping >= 1

Figure 4-22. Microsoft Excel 2007 Solver dialog box.

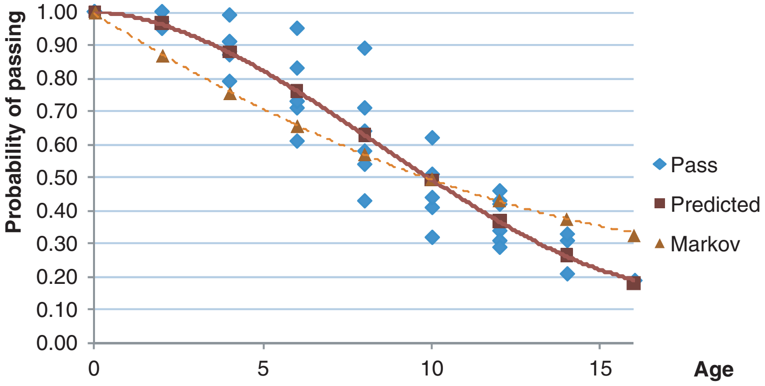


Figure 4-23. Comparing actual data (Pass) with Weibull model (Predicted) and Markov.

It can be seen in the graph that the Weibull survival probability model is a better fit to the data than the Markov model. Under the Markov model, the R-squared value is only 0.8081, and under the survival probability model, it is 0.9061.

The survival probability model has the same life expectancy as the Markov model, with a 50% probability of failure after 9.88 years; but there is less uncertainty in life expectancy: after 6 years, the Markov model predicts that 65.7% of the signs will pass, while the survival probability model predicts that 76.1% will pass. The Weibull model gives both a more accurate and more precise indication of when sign replacement will be needed.

For data sets where censoring is an issue (where it is not possible to use a database of retired assets to estimate the model), there are advanced techniques to correct for censoring bias. See Dodson (2006) for an extensive set of methods and examples.

Just like the Markov model, the survival probability model does not accommodate explanatory variables, but it is efficient in its use of data. Reliable models can be constructed with as few as 20 data points, provided the data set is carefully constructed to be representative of the population (Dodson 2006). When there is a need for explanatory variables, one simple approach is to partition the data set into subsets of the asset inventory distinguished by categorical data values, such as by district or climate zone.

For continuous explanatory variables, another approach is to use a linear multivariate model for the scaling parameter, as was done in several of the examples presented earlier in this chapter. The same maximum likelihood estimation technique then can be used for estimation of this model. Alternatively, a somewhat more elaborate model called a Cox model can be used, which follows.

4.2.4 Cox Survival Probability Model

The Cox proportional hazard model is very similar to a Weibull survival probability model, but it incorporates a multiplier to the survival probability to account for explanatory variables. The full equation for the Cox model is

$$y_{1g} = \exp\left(-1.0 \times (g/\alpha)^{\beta}\right) \times \exp\left(b_1 X_1 + b_2 X_2 + \cdots + b_n X_n\right)$$

where y_{1g} is the probability of the not-failed state at age g, if no intervening maintenance action is taken between year 0 and year g; β is the shaping parameter; and α is the scaling parameter, calculated as for the Weibull model. The variables X_n are explanatory variables such as traffic volume or location. They can be continuous variables or 0/1 flags. The coefficients b_n are determined by linear regression or can be estimated at the same time as the Weibull shaping parameter using Microsoft Excel's Solver. The multiplier can shift the survival probability either upward or downward. If all of the explanatory variables are zero, then the multiplier has no effect.

Table 4-31 uses the same data as Table 4-30, but includes explanatory variables for sun exposure and plywood backing. The spreadsheet model for estimating the Cox regression coefficients is very similar to the one used for the previous example, except for the use of the Cox equation and the additional explanatory variables. The results are shown on the right side of the table.

It can be seen in these results that the life expectancy estimate increased by a small amount, to 10.39 years. Also, the model is a better fit to the data, with an R-squared value of 0.9373. By taking advantage of additional data about the signs, it was possible to improve the quality of the model.

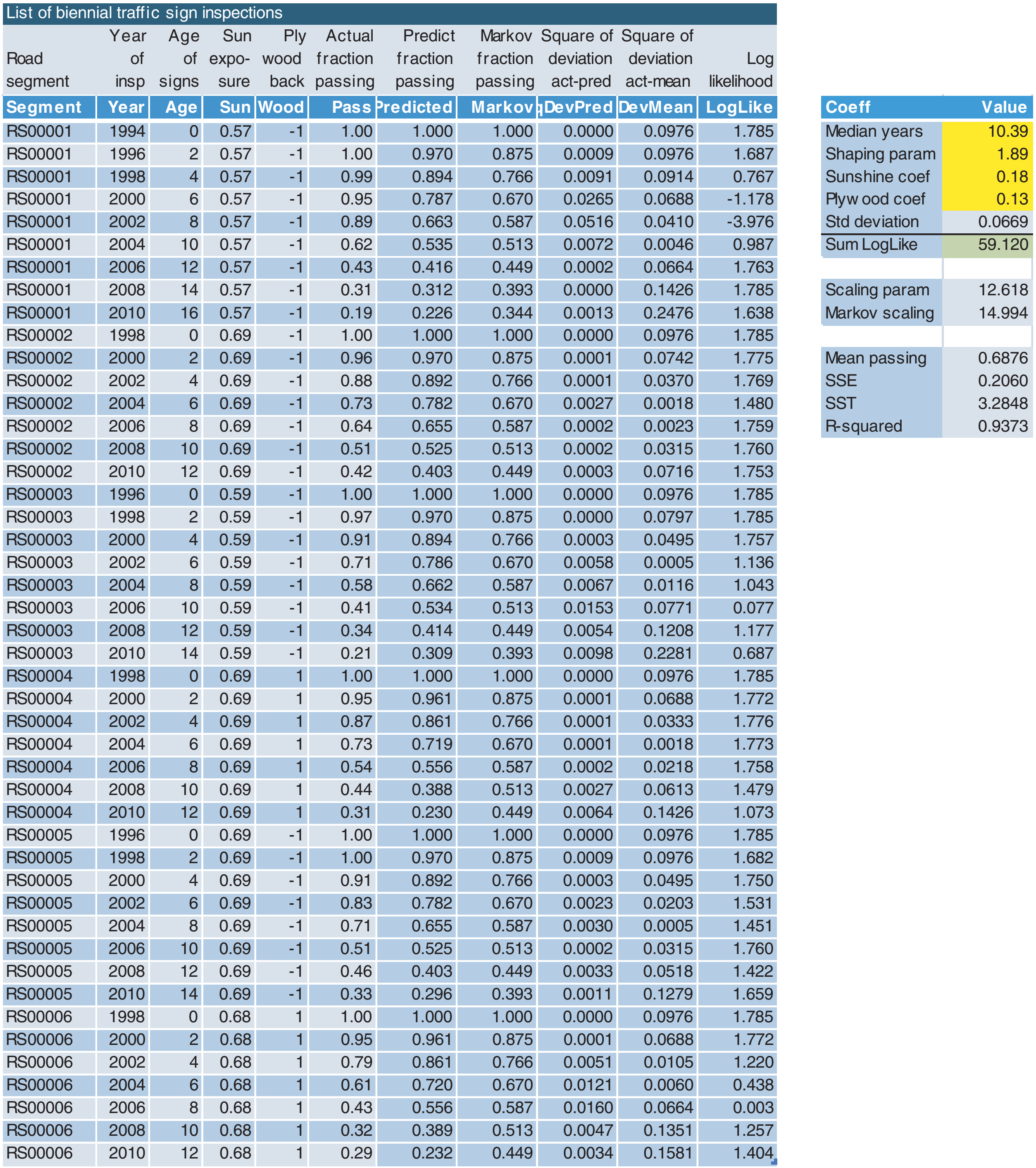
4.3 Validating and Refining Models

It is considered good practice in statistical analysis to divide the data set of inspection data into two subsets, one for model estimation and one for validation. The predictive models are developed using the first data set, then tested on the second data set to see if they produce accurate results (i.e., to check if their life expectancy estimates are correct). If the validation results are not "close enough," it might mean an error in the model development process. Typical causes of such errors might be

- Sample sizes that are too small. The Markov model typically needs a sample size of 100 inspection pairs or more. The Weibull and Cox models might need 200 or more for a realistic set of explanatory variables. If the model is partitioned, then each separate model needs to have a sufficient sample size.
- Too many explanatory variables. It is unusual for more than three or four explanatory variables to have a beneficial effect on the Cox model. After that, what appears to be a gain in performance might just be accidental correlation with randomness in the data. The ordinary regression model might be able to use five or six variables, but usually less are needed.
- Explanatory variables correlated with each other. If a model has both ADT and number of lanes as variables, for example, there is a good chance that the relationship between these two quantities will harm the performance of the model.
- Lack of variability in the data. If a data set has 1,000 inspection pairs, but they are all identical, then the model likely would not produce useful results.

- Lack of movement. If none of the inspection pairs show any deterioration, then the models would not work.
- Lack of population. If a condition state has no quantity entered, in the before case or the after case, then the model would not work.
- Lack of intuitive sense. In a regression model, it is easy to input every possible variable, just to see the results. Unfortunately, this could very likely produce misleading results. Only use variables that make intuitive sense.

Table 4-31. Cox regression model for signs.



List of biennial traffic sign inspections

Road segment	Year of insp	Age of signs	Sun expo-sure	Ply wood back	Actual fraction passing	Predict fraction passing	Markov fraction passing	Square of deviation act-pred	Square of deviation act-mean	Log likelihood
Segment	Year	Age	Sun	Wood	Pass	Predicted	Markov	qDevPred	DevMean	LogLike
RS00001	1994	0	0.57	-1	1.00	1.000	1.000	0.0000	0.0976	1.785
RS00001	1996	2	0.57	-1	1.00	0.970	0.875	0.0009	0.0976	1.687
RS00001	1998	4	0.57	-1	0.99	0.894	0.766	0.0091	0.0914	0.767
RS00001	2000	6	0.57	-1	0.95	0.787	0.670	0.0265	0.0688	-1.178
RS00001	2002	8	0.57	-1	0.89	0.663	0.587	0.0516	0.0410	-3.976
RS00001	2004	10	0.57	-1	0.62	0.535	0.513	0.0072	0.0046	0.987
RS00001	2006	12	0.57	-1	0.43	0.416	0.449	0.0002	0.0664	1.763
RS00001	2008	14	0.57	-1	0.31	0.312	0.393	0.0000	0.1426	1.785
RS00001	2010	16	0.57	-1	0.19	0.226	0.344	0.0013	0.2476	1.638
RS00002	1998	0	0.69	-1	1.00	1.000	1.000	0.0000	0.0976	1.785
RS00002	2000	2	0.69	-1	0.96	0.970	0.875	0.0001	0.0742	1.775
RS00002	2002	4	0.69	-1	0.88	0.892	0.766	0.0001	0.0370	1.769
RS00002	2004	6	0.69	-1	0.73	0.782	0.670	0.0027	0.0018	1.480
RS00002	2006	8	0.69	-1	0.64	0.655	0.587	0.0002	0.0023	1.759
RS00002	2008	10	0.69	-1	0.51	0.525	0.513	0.0002	0.0315	1.760
RS00002	2010	12	0.69	-1	0.42	0.403	0.449	0.0003	0.0716	1.753
RS00003	1996	0	0.59	-1	1.00	1.000	1.000	0.0000	0.0976	1.785
RS00003	1998	2	0.59	-1	0.97	0.970	0.875	0.0000	0.0797	1.785
RS00003	2000	4	0.59	-1	0.91	0.894	0.766	0.0003	0.0495	1.757
RS00003	2002	6	0.59	-1	0.71	0.786	0.670	0.0058	0.0005	1.136
RS00003	2004	8	0.59	-1	0.58	0.662	0.587	0.0067	0.0116	1.043
RS00003	2006	10	0.59	-1	0.41	0.534	0.513	0.0153	0.0771	0.077
RS00003	2008	12	0.59	-1	0.34	0.414	0.449	0.0054	0.1208	1.177
RS00003	2010	14	0.59	-1	0.21	0.309	0.393	0.0098	0.2281	0.687
RS00004	1998	0	0.69	1	1.00	1.000	1.000	0.0000	0.0976	1.785
RS00004	2000	2	0.69	1	0.95	0.961	0.875	0.0001	0.0688	1.772
RS00004	2002	4	0.69	1	0.87	0.861	0.766	0.0001	0.0333	1.776
RS00004	2004	6	0.69	1	0.73	0.719	0.670	0.0001	0.0018	1.773
RS00004	2006	8	0.69	1	0.54	0.556	0.587	0.0002	0.0218	1.758
RS00004	2008	10	0.69	1	0.44	0.388	0.513	0.0027	0.0613	1.479
RS00004	2010	12	0.69	1	0.31	0.230	0.449	0.0064	0.1426	1.073
RS00005	1996	0	0.69	-1	1.00	1.000	1.000	0.0000	0.0976	1.785
RS00005	1998	2	0.69	-1	1.00	0.970	0.875	0.0009	0.0976	1.682
RS00005	2000	4	0.69	-1	0.91	0.892	0.766	0.0003	0.0495	1.750
RS00005	2002	6	0.69	-1	0.83	0.782	0.670	0.0023	0.0203	1.531
RS00005	2004	8	0.69	-1	0.71	0.655	0.587	0.0030	0.0005	1.451
RS00005	2006	10	0.69	-1	0.51	0.525	0.513	0.0002	0.0315	1.760
RS00005	2008	12	0.69	-1	0.46	0.403	0.449	0.0033	0.0518	1.422
RS00005	2010	14	0.69	-1	0.33	0.296	0.393	0.0011	0.1279	1.659
RS00006	1998	0	0.68	1	1.00	1.000	1.000	0.0000	0.0976	1.785
RS00006	2000	2	0.68	1	0.95	0.961	0.875	0.0001	0.0688	1.772
RS00006	2002	4	0.68	1	0.79	0.861	0.766	0.0051	0.0105	1.220
RS00006	2004	6	0.68	1	0.61	0.720	0.670	0.0121	0.0060	0.438
RS00006	2006	8	0.68	1	0.43	0.556	0.587	0.0160	0.0664	0.003
RS00006	2008	10	0.68	1	0.32	0.389	0.513	0.0047	0.1351	1.257
RS00006	2010	12	0.68	1	0.29	0.232	0.449	0.0034	0.1581	1.404

Coeff	Value
Median years	10.39
Shaping param	1.89
Sunshine coef	0.18
Plywood coef	0.13
Std deviation	0.0669
Sum LogLike	59.120
Scaling param	12.618
Markov scaling	14.994
Mean passing	0.6876
SSE	0.2060
SST	3.2848
R-squared	0.9373

A good way to determine whether a life expectancy model will work in practice is to start with a quick-and-easy version of the model, and then build it into a prototype of the envisioned application. Microsoft Excel is a good way to do this because development and refinement in Microsoft Excel can be done very quickly. This exercise will help the analyst see all the way through the problem, from raw data to finished product. This experience often leads to design changes that vastly improve the product.

To visualize the accuracy of the model, a common technique is validation plots. These plots vary by the type of model calibrated. To validate the developed techniques, it is recommended to randomly split the data set in two, with one set used for calibration and the other purely for validation. The assessment of the model is then typically evaluated by plotting the predictions of the validation set using the calibrated model to the observed value from the validation set (Figure 4-24). The closer the data points to the straight line, the better the fit.

The proportion of the data set used for validation is subject to expert opinion. A typical proportion may be 75% calibration, 25% validation. However if there is a lack of available data for calibration, a greater percentage may be used for calibration. Conversely, for large data sets a much smaller percentage may be appropriate for calibration. When validating probabilistic models, a similar technique can be applied by comparing survival curves to non-parametric estimates such as the Kaplan-Meier estimate or non-homogenous Markov chain.

Statistical analysis is part science and part art, with a lot of opportunity for creativity and a lot of room for error. To ensure that the results of the life expectancy analysis are intuitive and can be implemented, it is helpful to solicit advice from experienced modelers and users of these models. The presence of outlying data is an important issue that requires careful treatment and may warrant the solicitation of expert opinion. The presence of outliers may greatly influence model parameters and may result in models with low goodness-of-fit measures. On the other hand, outright exclusion of outliers may lead to the unintended suppression of important information which may adversely affect the model reliability.

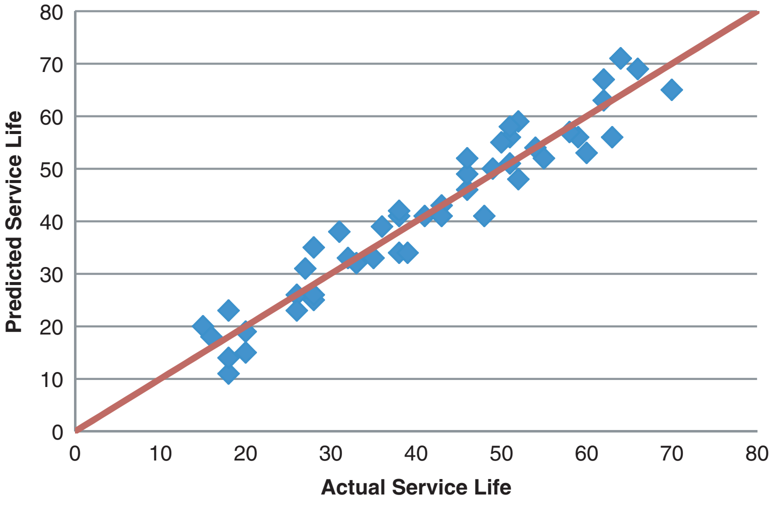


Figure 4-24. Example validation plot.

CHAPTER 5

Develop Applications: How to Apply Life Expectancy Models

Many of the objectives of life expectancy analysis go beyond the simple calculation of life span. Agencies that gather the necessary data and perform the analysis can benefit in many more ways by constructing useful applications that go farther, to help in developing and selecting policies, planning future work programs, and developing cost-effective designs and projects. This is all a part of the advancements in asset management maturity.

This chapter will show how tools built on top of the same building blocks as life expectancy analysis can fill the gap between management needs and data collection. Such applications help to turn data into useful information, which in the hands of proactive management can improve the agency's efficiency and effectiveness in accomplishing its mission (Figure 5-1). This chapter presents the main building blocks: deterioration models, equivalent age, life extension, asset life, and lifecycle cost. It then presents some sample applications. It concludes with guidance on the process for designing, developing, and refining life expectancy applications.

5.1 Deterioration Models and Life Expectancy

Chapter 4 showed the most direct ways to proceed from available data to estimates of life expectancy for the most common types of highway assets. In most cases, agencies will want to go farther, to put their knowledge of life expectancy to work to assist with asset management decision-making, for example, by developing additional tools.

Life expectancy is just a part of a larger investigation of deterioration (Figure 5-2). For pavements and bridges, deterioration models have become quite mature, are very widely used, and often form the basis of life expectancy estimates; but deterioration models can be developed for any type of asset, by building on the methods already covered.

Deterioration models are used to forecast decline in condition in the absence of corrective action by the agency. More general than life expectancy models, they forecast not only the end-of-life, but all other possible condition levels as well. In many cases, agencies determine life expectancy from their deterioration models. The existence of a deterioration model can improve the accuracy and/or precision of life expectancy estimates.

5.1.1 Regression of Condition

Deterministic models are among the oldest techniques in use for deterioration modeling. These models directly predict the most likely value of a condition measure as a function of age and other explanatory variables. This is done by means of a straight or curved line, whose shape and parameters are set by a regression process.

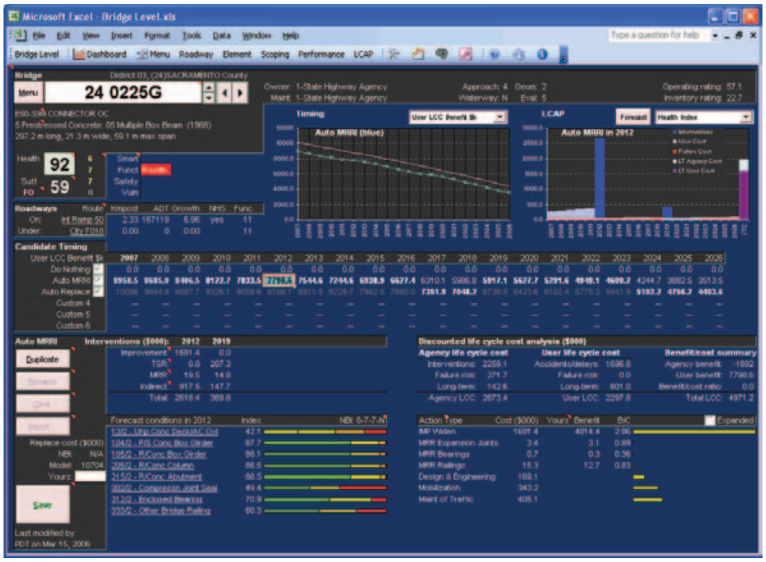


Figure 5-1. Applications put the models to work on day-to-day asset management problems (Patidar et al. 2007).

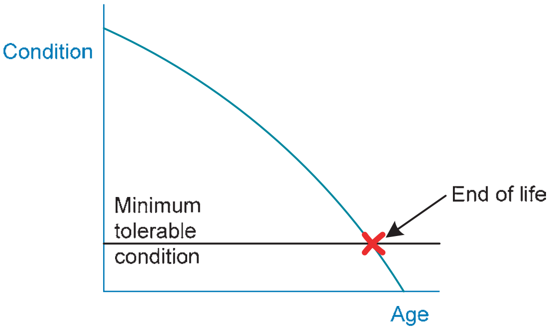


Figure 5-2. Life expectancy as a part of deterioration modeling.

Deterministic models were popular before 1960 when they were developed by the AASHO Road Test (before AASHO became AASHTO) for pavements (Patterson 1987). This produced the iconic shape (Figure 5-3) that is still associated with all types of infrastructure deterioration, even though the original AASHO curve is rarely used today. The equation for the AASHO curve is

$$p_t = p_0 - \left(p_0 - p_f\right)\left(\frac{t}{\rho}\right)^{\alpha}$$

where p_t is performance at time t; p_0 is initial performance; p_f is terminal performance; t is the year of the forecast; ρ is lifespan; and α is the shaping parameter.

Because the basic model lacks explanatory variables, it is easy to develop. The life span estimate can be produced by any of the methods discussed so far in this guide and can be a function of explanatory variables or a partitioned data set if desired. The shaping parameter can be determined by linear regression, if life span is known and is not believed to vary much from one agency to another. Subsequent enhancements made the curve "s-shaped" so it would approach the terminal performance level asymptotically.

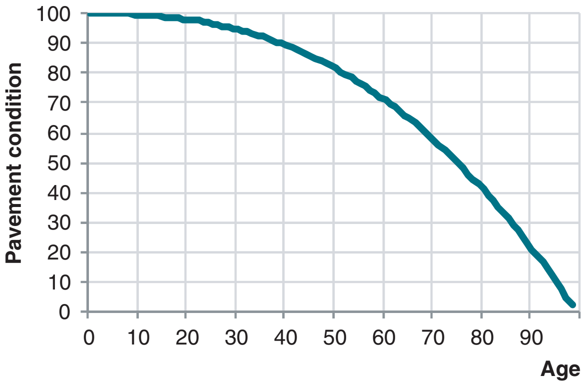


Figure 5-3. AASHO Road Test pavement deterioration model.

Subsequent research efforts have developed various forms of non-linear deterioration curves that resembled the AASHO curve and could include explanatory variables such as traffic and climate, but which still can be estimated using simpler linear regression techniques. Life expectancy could be read off the curve where it intersected the minimum tolerable condition level or by inverting the equation to make age a function of condition.

Despite the apparent simplicity of the deterministic deterioration curve, the model has some drawbacks which limit the ability to improve it or build useful applications with it:

- It requires a continuous variable as the condition measure. Many agencies use PCR and/or IRI as condition measures for pavements. A few agencies use retroreflectivity for signs and pavement markings. Other than these examples, the use of continuous condition measures is relatively unusual in asset management, due to the cost of data collection using specialized equipment.
- Commonly used regression models assume that variability is constant along the regression line and produce very little useful output about uncertainty. The assumptions about variability are often far off the mark and cause severe inaccuracies in the models. For many of the most useful applications, information about uncertainty is a necessity.
- If life expectancy is the main output desired, there are even simpler ways of estimating it that do not require a regression model. Chapter 4 described those methods.

A great many regression models for bridge deterioration, based on NBI condition ratings, can be found in the research literature. In the relatively few cases where these models have been tested and validated, they have not performed well because the NBI rating scale is discrete, not continuous. The research work accompanying this guide investigated the issue and found that other types of models produced more accurate forecasts.

Even for continuous condition measures, linear regression models can be problematic. For example, a regression model of past pavement performance data from a North Carolina DOT division was developed by the researchers. The dependent variable was PCR, measured on a range of 0–100 where 0 means worst and 100 means best. The resulting equation was

$$\text{PCR} = 90.33 - 2.94 * \text{Age} + 5.37 * \text{Jurisdiction} + 0.112/\text{ADT} + 2.27 * \text{Resurfacing\_Thick}$$

where

Age = age in years since last resurfacing;
Jurisdiction = 1 if sub-divisional; 0 if rural;
ADT = average daily traffic in thousands;
Resurfacing_Thick = thickness of last resurfacing in inches.

The model's adjusted R^2 was found to be 0.30 with significant autocorrelation problems, suggesting that linear regression is not an appropriate life expectancy method for the given data in the example application.

5.1.2 Markov Models

Most common asset management processes use categorical data, which classify condition into a relatively small number of categories. In part, this results from the use of visual inspection techniques, which can only discern a few gradations reliably. Another motivation is the common popular use of categorical value measures, such as good-fair-poor, or A-B-C-D-F. The simplest commonly used deterioration modeling technique for this type of data is the Markov model.

As explained in Chapter 4, a Markov model requires consistent use of a condition state assessment scheme and a uniform time interval between observations and assumes that the probability of making a transition from one condition state to another depends only on the initial state, rather than on age, past conditions, or any other information about the element. Thus, the model is expressed as a simple matrix of probabilities (Table 5-1).

A Markov model is a cross-sectional model, able to be developed from a population of assets even if they have not been inspected consistently over their whole lives. This is especially useful for structures whose lives can extend to 50–100 years or more, where a full time series data set is not obtainable.

A Markovian transition probability matrix is a special type of matrix with a number of desirable properties that make it easy to process. A well-formed transition probability matrix adheres to the following rules:

1. Square matrix—All transition probability matrices are square, with the number of rows and the number of columns both equal to the number of possible condition states.
2. Upper-right triangular—Only the main diagonal and the upper-right triangle of the matrix are allowed to have non-zero values. This is another way of saying that there can be no movement from any condition state to a better state in a deterioration model.
3. Non-negative—No elements of the matrix may be negative.
4. Positive diagonal—Elements on the diagonal must be non-zero. In other words, there must be a non-zero possibility of remaining in the same condition state from one inspection to the next.
5. Normalized—All rows of the matrix must separately sum to 100%. In other words, the transition probability matrix must account for all possible transitions.
6. Because of the combination of these rules, the lower right corner element must be 100%. Once an asset deteriorates to the worst condition state, it stays there.

Table 5-1. Example Markov deterioration model.

		Probability of each condition state one year later (%)				
		1	2	3	4	5
Condition state now	1	95.3	4.6	0.1	0	0
	2	0	93.2	3.9	1.9	1.0
	3	0	0	89.4	7.3	3.3
	4	0	0	0	82.8	17.2
	5	0	0	0	0	100

A transition probability matrix can have as few as two condition states, such as pass/fail. It commonly has four or five states for most types of assets. For pavements, there are examples in Arizona, Kansas, and Finland of more than 100 condition states. In those cases, condition is measured on multiple dimensions. For example, if there are five states of roughness, five states of cracking, and five states of rutting, then the deterioration model has 125 rows and 125 columns.

Conditions in any future year can be predicted with a Markovian model by simple matrix multiplication. Mathematically, the matrix multiplication for Markovian prediction, when no maintenance action is taken, looks like this:

$$y_k = \sum_j x_j p_{jk} \text{ for all } k$$

where x_j is the probability of being in condition state j at the beginning of the year; y_k is the probability of being in condition state k at the end of the year; and p_{jk} is the transition probability from j to k. This computation can be repeated to extend the forecast for additional years. An example of this computation was shown above in Table 4-28.

It is possible to derive transition probabilities if the median number of years between transitions is known. Often this is an appropriate way to develop a deterioration model from expert judgment. It also provides a convenient means of computing, storing, and reporting transition probabilities derived from historical inspection data. If it takes t years for 50% of a population of elements to transition from state j to state $k = j + 1$, and no other transitions are possible, then the one-year transition probabilities are

$$p_{jj} = 0.5^{(1/t)} \text{ and } p_{jk} = 1 - p_{jj}$$

So if it takes a median of 10.23 years to transition from state 1 to state 2, then the probabilities after 1 year are 93.4% for state 1 and 6.6% for state 2.

5.1.2.1 Data Preparation

The first step in developing a Markov model is to gather a set of inspections for a large group of assets. Each asset must have at least two inspections. It is not necessary to be able to follow any one asset through its whole life, but it is necessary for all possible condition states to be observed somewhere in the data set.

Inspections are grouped into pairs, each pair showing the change in condition of an asset (or bundle of assets, such as all the traffic signal heads in one intersection, or all the girders on one bridge) over a period of time. Each inspection can be the beginning of one or more pairs and the end of one or more pairs. The pairs must be uniform in length, commonly either 1 year or 2 years, plus or minus 6 months. If the inspection intervals in the data set are not uniform, it is possible to interleave inspection pairs (Figure 5-4).

The deterioration model is intended to describe changes in condition if no agency action is taken to try to improve the condition of the asset. Therefore, it is necessary to remove from the data set any pairs that had agency corrective action between the two inspections. One way to determine this fact is to consult the agency's information systems where records of past activities are maintained. In practice, this is often an imperfect record of activity.

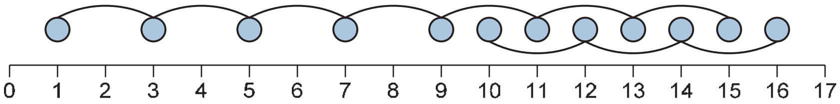


Figure 5-4. Interleaved inspection pairs.

Another way to detect possible repair activity is to look for improvements in condition. The following formula can be calculated for each inspection pair:

$$IC = \max_j \left(\sum_{k=1}^{j} y_k - \sum_{k=1}^{j} x_k \right)$$

where *IC* is the improvement in condition for the inspection pair; *j* and *k* are condition states defined for the asset that was inspected (assuming that k = 1 is the best possible condition state); $\max_j$ indicates maximization over all possible condition states of the asset; y_k is the fraction of the asset in condition state k in the second inspection of the pair; and x_k is the fraction of the asset in condition state k in the first inspection of the pair.

This equation quantifies improvement as the increase in the fraction at, or better than, any given condition state. Computed over all condition states, the largest increase is selected to represent the inspection pair as its maximum condition improvement. If any one or more of the condition states shows an increase in the fraction at its level or better, then *IC* is positive. This can indicate either that an error occurred in the inspection process or a preservation activity took place. In the absence of reliable maintenance records, the analyst will often need to assume that all positive *IC* values indicate repair activity and will remove all such pairs from the data set.

5.1.2.2 Linear Regression

One relatively easy way to determine the transition probabilities from the list of inspection pairs is linear regression (Cambridge 2003), using the following steps.

Conditions at the beginning of the period:

$$[X] = \{x_1^i, x_2^i, x_3^i, x_4^i, x_5^i\} \text{ for all inspection pairs } i$$

Conditions at the end of the period:

$$[Y] = \{y_1^i, y_2^i, y_3^i, y_4^i, y_5^i\} \text{ for all inspection pairs } i$$

These are the known values in the estimation equation. The prediction equation is

$$[Y] = [P][X]$$

where $[P]$ is the transition probability matrix. The unknown transition probabilities can be estimated:

$$[\bar{P}] = [XX]^{-1}[XY]$$

Matrix of XX sums:

$$[XX] = \sum_i x_j^i x_k^i \text{ for all combinations of j and k}$$

Matrix of XY sums:

$$[XY] = \sum_i x_j^i y_k^i \text{ for all combinations of j and k}$$

The exponent on $[XX]^{-1}$ indicates matrix inversion. Following the regression computation, the resulting matrix is normalized to ensure that it satisfies the rules of a well-formed transition probability matrix. Any values to the left of the diagonal are set to zero. If any diagonal elements are less than 0.01, they are changed to 0.01 (or some other small positive value). Negative values to the right of the diagonal are set to zero. Then each row is adjusted to sum to 1.0:

$$p'_{jk} = \frac{p_{jk}}{s_j} \qquad s_j = \sum_k p_{jk}$$

A strong point of the regression method is that it can estimate the probabilities of transition from any starting state to any worse state. The upper-right triangle of the matrix can consist of all positive numbers. This is useful for short-lived assets where a jump of two or more condition states is not unusual between inspections. A weakness of the method is that it is subject to various numerical problems with the matrix inversion step, which can yield incorrect results or fail to produce a result. Thus, the results need careful scrutiny for reasonableness.

5.1.2.3 One-Step Method

For long-lived assets, where the inspection interval is short in comparison to the life span, jumps of more than one state at a time may be unusual. In fact, it may be impossible if only two states, such as pass/fail, are used. In this case, the estimation process can be simplified into the one-step method (Thompson and Sobanjo 2010).

To set up the estimation of a one-step matrix, the prediction equation is defined as follows, for an example with four condition states:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} & 0 & 0 \\ & p_{22} & p_{23} & 0 \\ & & p_{33} & p_{34} \\ & & & p_{44} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

Writing out the individual equations necessary to calculate $[Y]$ results in

$$y_1 = x_1 p_{11}$$

$$y_2 = x_1 p_{12} + x_2 p_{22}$$

$$y_3 = x_2 p_{23} + x_3 p_{33}$$

$$y_4 = x_3 p_{34} + x_4 p_{44}$$

Given that the sum of each row in $[P]$ must be 1.0, the following additional equations apply:

$$p_{12} = 1 - p_{11};\ p_{23} = 1 - p_{22};\ p_{34} = 1 - p_{33}$$

The vectors $[X]$ and $[Y]$ can be computed from the database of inspection pairs to describe the combined condition of the element before and after:

$$[X] = \frac{1}{N}\sum_{i=1}^{N} x_j^i, [Y] = \frac{1}{N}\sum_{i=1}^{N} y_j^i \text{ for all condition states } j$$

where N is the number of inspection pairs. So the $[X]$ and $[Y]$ vectors are known. Thus, the system of seven equations and seven unknowns can be solved algebraically for the elements of $[P]$. This same pattern applies for any number of condition states.

Table 5-2 shows an example of the one-step method. The first section is the table of original inspection pairs, showing the data preparation to eliminate pairs that improved in condition.

Table 5-2. Example of the one-step method of estimating Markov models.

Inspection pairs															
	Condition - start of year					Condition - end of year					Improvement in condition				
Road segment	Insp Year	Condition state 1	2	3	4	Condition state 1	2	3	4		Condition state 1	2	3	4	Screening
RS0028	2004	92	8	0	0	82	17	1	0		-10	-1	0	0	
RS0028	2005	82	17	1	0	68	27	4	1		-14	-4	-1	0	
RS0028	2006	68	27	4	1	58	32	9	1		-10	-5	0	0	
RS0028	2007	58	32	9	1	48	37	11	4		-10	-5	-3	0	
RS0028	2008	48	37	11	4	46	35	12	7		-2	-4	-3	0	
RS0028	2009	46	35	12	7	37	39	14	10		-9	-5	-3	0	
RS0028	2010	37	39	14	10	32	37	19	12		-5	-7	-2	0	
RS0061	2005	100	0	0	0	84	16	0	0		-16	0	0	0	
RS0061	2006	84	16	0	0	78	19	3	0		-6	-3	0	0	
RS0061	2007	78	19	3	0	67	27	5	1		-11	-3	-1	0	
RS0061	2008	67	27	5	1	65	23	10	2		-2	-6	-1	0	
RS0061	2009	65	23	10	2	55	28	12	5		-10	-5	-3	0	
RS0061	2010	55	28	12	5	53	24	15	8		-2	-6	-3	0	
RS0035	2004	83	10	5	2	75	17	5	3		-8	-1	-1	0	
RS0035	2005	75	17	5	3	68	20	7	5		-7	-4	-2	0	
RS0035	2006	68	20	7	5	63	24	7	6		-5	-1	-1	0	
RS0035	2007	63	24	7	6	52	32	7	9		-11	-3	-3	0	
RS0035	2008	52	32	7	9	43	36	10	11		-9	-5	-2	0	
RS0035	2009	43	36	10	11	37	39	11	13		-6	-3	-2	0	
RS0035	2010	37	39	11	13	33	34	18	15		-4	-9	-2	0	
RS0011	2005	29	21	18	32	25	22	17	36		-4	-3	-4	0	
RS0011	2006	25	22	17	36	24	18	18	40		-1	-5	-4	0	
RS0011	2007	24	18	18	40	100	0	0	0		76	58	40	0	Delete
RS0011	2008	100	0	0	0	83	17	0	0		-17	0	0	0	
RS0011	2009	83	17	0	0	77	22	1	0		-6	-1	0	0	
RS0011	2010	77	22	1	0	73	23	3	1		-4	-3	-1	0	
RS0001	2003	100	0	0	0	86	14	0	0		-14	0	0	0	
RS0001	2004	86	14	0	0	75	22	3	0		-11	-3	0	0	
RS0001	2005	75	22	3	0	63	31	5	1		-12	-3	-1	0	
RS0001	2006	63	31	5	1	62	26	10	2		-1	-6	-1	0	
RS0001	2007	62	26	10	2	51	33	12	4		-11	-4	-2	0	
RS0001	2008	51	33	12	4	49	33	10	8		-2	-2	-4	0	
RS0001	2009	49	33	10	8	42	36	11	11		-7	-4	-3	0	
RS0001	2010	42	36	11	11	35	36	15	14		-7	-7	-3	0	
RS0004	2006	24	18	15	43	21	18	15	46		-3	-3	-3	0	
RS0004	2007	21	18	15	46	18	17	15	50		-3	-4	-4	0	
RS0004	2008	18	17	15	50	16	15	15	54		-2	-4	-4	0	
RS0004	2009	16	15	15	54	90	10	0	0		74	69	54	0	Delete
RS0004	2010	90	10	0	0	79	19	2	0		-11	-2	0	0	
RS0016	2006	81	14	4	1	76	18	4	2		-5	-1	-1	0	
RS0016	2007	76	18	4	2	62	30	5	3		-14	-2	-1	0	
RS0016	2008	62	30	5	3	59	29	7	5		-3	-4	-2	0	
RS0016	2009	59	29	7	5	55	31	8	6		-4	-2	-1	0	
RS0016	2010	55	31	8	6	51	28	13	8		-4	-7	-2	0	

Change in condition for segments where no work done								
	Condition at start				Condition at end			
	1	2	3	4	1	2	3	4
Avg by state	62.6	22.6	7.0	7.9	55.4	26.2	8.8	9.6

Computed transition probabilities using One-Step Method				
	Condition state probabilities			
	1	2	3	4
Stay in same state	88.5	84.2	74.7	100
Deteriorate one step	11.5	15.8	25.3	0.0

The second section contains the $[X]$ and $[Y]$ vectors, and the third section shows the results, the non-zero members of the transition matrix.

5.1.2.4 Life Expectancy from Markov Deterioration

Chapter 4 showed how any set of condition states can be collapsed into two states, failed and not-failed, after which a version of the one-step method can be used to compute transition probabilities and life expectancy, with the formula

$$t = \frac{\log(0.5)}{\log(p_{jj})}$$

This method was called "quick and easy" mainly because of the collapsing of condition states, which then requires the assumption that all assets in the not-failed state are equally likely to fail in the next year.

A Markov model for the full set of condition states improves on this result because only the assets currently in the second-to-last condition state are in position to possibly reach the worst state in the following year. If the not-failed assets are currently concentrated in the best condition state, it will be many years before very many of them reach the worst state. As a result, life expectancy forecasts made with the help of a fully-developed Markov model can be more accurate than the quick-and-easy method.

To calculate life expectancy from a Markov transition probability matrix, start with an asset in perfect condition and repeatedly multiply by the transition probability matrix until 50% of the asset is in the worst condition state. Table 4-28 shows an example.

5.1.3 Markov/Weibull Models

In Chapter 4, the Weibull survival probability model was used to give an age-dependent probability of failure for the failed/not-failed scenario as an enhancement of the Markov model. The Weibull model can play a similar role in a deterioration model.

One useful application for this enhancement is in modeling the onset of deterioration, the transition from the best condition state to the second-best state. This is analogous to the transition from the not-failed state to the failed state and is mathematically the same model. The only difference is that the median state transition time is used instead of the median life expectancy. As shown in Figure 5-5, the Markov model features a rather quick decline in condition, even for a brand new asset, an effect not often observed in practice. The Weibull model can slow the onset of deterioration, making the initial stages of the deterioration model more realistic.

Another useful application for the Weibull model in life expectancy analysis is in modeling the transition from the second-worst condition state to the worst (failed) state. The Markov model provides a median transition time, but the Weibull model can refine this estimate and provide a measure of uncertainty in the time to failure. So for assets already in the second-worst state, the Weibull model can provide an estimate of what fraction of them will fail within a defined time period, such as a 2-year budget or a 10-year program horizon. This can help to make budgeting more accurate. The methods for computing these estimates are the same as described in Chapter 4.

It is possible to develop a completely age-dependent Weibull survival probability deterioration model if all of the individual state transitions can be analyzed independently, that is, if each asset is in only one condition state at a time and can move to only one other state between inspections. These conditions do not hold true for bridges, where AASHTO CoRe Elements are described as a distribution of members among condition states (with the notable exception of New York in

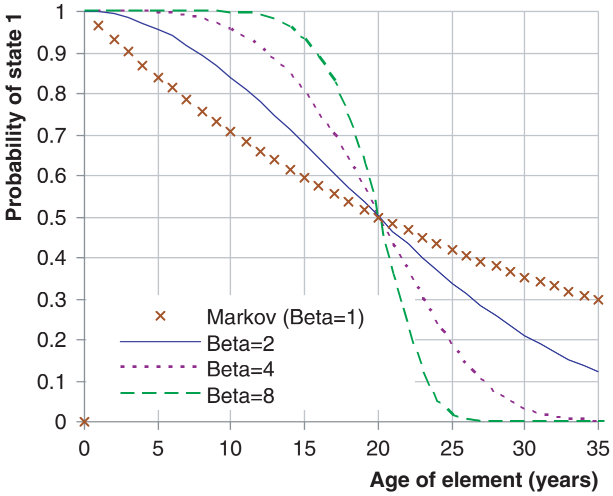


Figure 5-5. Comparison of the Markov and Weibull models.

Agrawal and Kawaguchi 2009). For other types of assets, tracking each individual piece of equipment separately may involve more data collection and management than most agencies would want to undertake. For most cases, securing an age-dependent deterioration model requires more powerful tools.

5.1.4 Ordered Probit

Another condition-based approach that could be used by agencies for deterioration prediction is the ordered probit model. This model can be used to produce age-dependent performance curves for assets with discrete, ordered condition states such as the NBI 0–9 rating system.

The likelihood of being in any condition state at a time *t* can be determined as a function of a set of life expectancy factors, an asset's age, and a set of threshold parameters. These threshold parameters, μ, serve as a sort of boundary between condition states.

For instance, consider the pipe culvert 0–3 rating scale discussed in Section 4.1.1.5. Depending on the model sum ($\Sigma\beta x$) and the threshold parameters (μ), the probability of being in a condition state will differ according to a normal distribution (Figure 5-6).

Mathematically, the exact probability of an asset being in any condition state follows the cumulative standard normal distribution with the variable *X* taking the following forms:

$$P(Condition\ State=0)=\left[-\sum\beta x\right]\sim N(0,1)$$

$$P(Condition\ State=1)=\left[\mu_1-\sum\beta x\right]\sim N(0,1)-\left[-\sum\beta x\right]\sim N(0,1)$$

$$P(Condition\ State=2)=\left[\mu_2-\sum\beta x\right]\sim N(0,1)-\left[\mu_1-\sum\beta x\right]\sim N(0,1)$$

$$P(Condition\ State=3)=1-\left[\mu_2-\sum\beta x\right]\sim N(0,1)$$

where

$P(Condition\ State=i)$ = Predicted probability of an asset being in condition state *i*;
x = set of independent variables, age, material type, etc.;
β = set of parameter estimates corresponding to independent variables;

μ = threshold parameters, which in comparison to parameter estimates and variable values, indicate the likelihood of being in a given condition state;

$[\mu - \Sigma\, \beta x]$ = X value that can be used to calculate normal distribution test statistic via

$$Z = \frac{X - Mean}{Standard\ Deviation}$$

$N(0, 1)$ = indicates the cumulative, standard normal distribution with mean = 0 and standard deviation = 1

By using age as an independent variable in the model, it is possible to make a condition state prediction for each asset across every feasible age while holding all other variables constant. For instance, suppose we calibrated an ordered probit model for pipe culverts with

$$\sum \beta x = 2.444;\ \mu_0 = 0;\ \mu_1 = 1.116;\ \mu_2 = 2.221$$

Using the model, the probability of the culvert asset being in each condition state can be determined as follows:

$$P(Condition\ State = 0) = [-2.444] \sim N(0,1)$$

Using Excel, = NORMDIST$(-2.444, 0, 1, 1) = 0.0073$

$$P(Condition\ State = 1) = [1.116 - 2.444] \sim N(0,1) - [-2.444] \sim N(0,1)$$

Using Excel, = NORMDIST$(1.116 - 2.444, 0, 1, 1)$ − NORMDIST$(-2.444, 0, 1, 1) = 0.0848$

$$P(Condition\ State = 2) = [2.221 - 2.444] \sim N(0,1) - [1.116 - 2.444] \sim N(0,1)$$

Using Excel, = NORMDIST$(2.221 - 2.444, 0, 1, 1)$ − NORMDIST$(1.116 - 2.444, 0, 1, 1) = 0.3198$

$$P(Condition\ State = 3) = 1 - [2.221 - 2.444] \sim N(0,1)$$

Using Excel, = 1 − NORMDIST$(2.221 - 2.444, 0, 1, 1) = 0.5881$

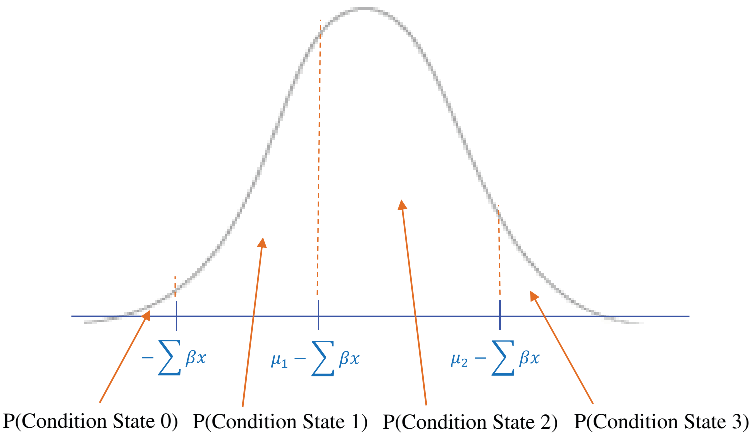


Figure 5-6. Example illustration of an ordered probit model with μ_0 = 0 for pipe culverts *(after Washington et al. 2003).*

In other words, the culvert in this specific example is considered to have a 0.73% chance of being in condition state 0, an 8.48% chance of being in condition state 1, a 31.98% chance of being in condition state 2, and a 58.81% chance of being in condition state 3. Therefore, the most likely condition state for this asset is condition state 3. If the same calculations are repeated for different ages resulting in different model sums, then a performance curve like the one in Figure 5-7 can be obtained.

5.1.5 Machine Learning

An even more mathematically complex technique for life prediction that has gained popularity among some researchers that could be considered by agencies is machine learning. Essentially, this non-linear, adaptive model predicts conditions based on what it has "learned" (pattern identification) from past data. Statistically, an artificial neural network (the most common learning technique) is a non-linear form of 3-Stage Least Squares regression, where "instruments" (variables used to represent relationships between other variables) are estimated to predict future events (Figure 5-8).

To facilitate learning, such models are typically Bayesian-based. This approach updates estimates (i.e., posterior means) by applying weighted averages based on previous estimates

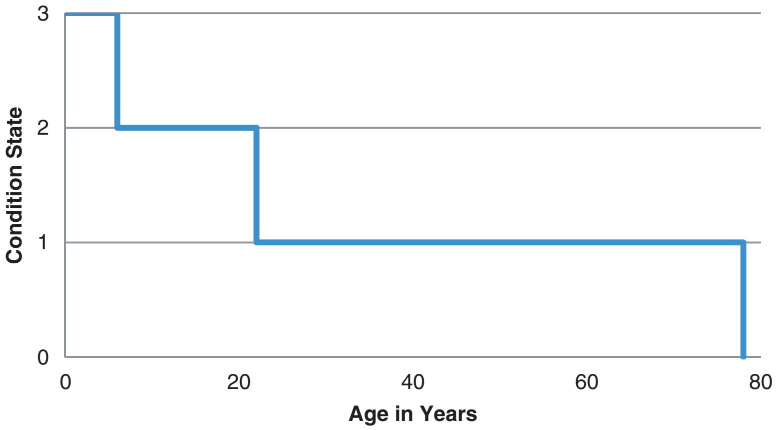


Figure 5-7. Example pipe culvert performance function using the ordered probit model.

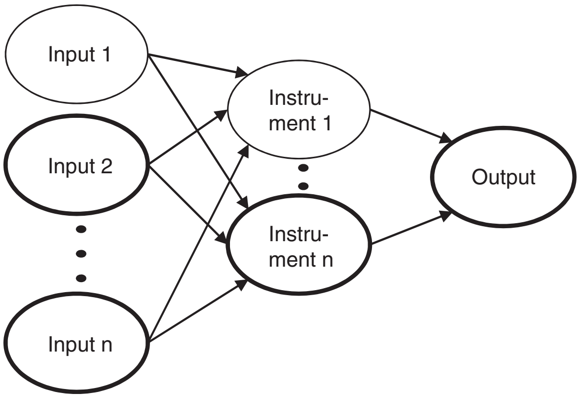


Figure 5-8. Example of an artificial neural network.

(i.e., prior means). Typically, these weights are based on the number of observations. Activation functions within the network have included hyperbolic tangent, log-sigmoid, and bipolar-sigmoid functions. Such approaches have been found to work well with noisy data and are relatively quick; however, such techniques are better suited for smaller databases (Melhem and Cheng 2003). These models require more sophisticated software to develop and sometimes can be used as a "black box" (i.e., prediction process unknown but assumed appropriate). However, the ability to "learn" makes these models particularly useful to asset managers in applications where it is necessary to adjust predictions in real time in response to new data, such as inputs from monitoring systems. Such an approach is outside the scope of this guide, but interested managers may want to consider applying machine learning to their databases.

5.1.6 Mechanistic Models

This guide emphasizes empirical models; however, some agencies prefer to define life more directly in terms of structural response. For instance, bridge life may be reached at the time the reliability of members to resist shear and strain stresses reaches a threshold level. Another example would be predicting pipe culvert life based on the time until corrosion based on the resistivity of a material to chloride ions. Such techniques may be difficult to apply at the network level, requiring extensive data on asset dimensions and conditions, and do not account for alternative replacement rationale. Regardless, the condition-based and interval-based methodologies proposed in this guide can still apply to the results of mechanistic models.

5.2 Building Blocks of Life Expectancy Applications

The techniques of life expectancy analysis and deterioration models open the door for various useful applications to support asset management decision-making. Before introducing these applications, it is useful to develop a few additional building blocks that make it easier to understand and construct these applications.

5.2.1 Equivalent Age

Deterioration models are often used to convert from the age of an asset to a forecast of its condition. But many applications also need the opposite capability, namely, to convert from a known condition to an equivalent age. How this is done depends on the type of deterioration model used.

5.2.1.1 Deterministic Models

For a deterministic model of condition versus age, such as the AASHO curve, it is usually a simple matter to read the age from the curve for any level of condition. Many functional forms can be inverted to make age the dependent variable of the equation. Even if this is not possible, the equivalent age can be found numerically by iterating through the range of possible ages until the desired condition level is found.

5.2.1.2 Markov Models

Converting from a condition state representation to an equivalent age is somewhat more challenging. If an individual asset is rated in just one state or another at a given point in time, then its condition state may correspond to a range of years in the deterioration model. In the more common case where the unit of analysis is a bundle of assets, multiple condition states may be included in the bundle. In that case, the equivalent age depends on the relative fractions in each condition state.

One way to minimize the complication is to use the Markov prediction formula iteratively until the 50% failure criterion is reached. As long as the asset has not already reached its life expectancy, the remaining life can be determined in this way and then subtracted from the life expectancy to compute equivalent age.

To forecast the condition state 1 year following a known condition, the formula is

$$y_k = \sum_j x_j p_{jk} \qquad \text{for all } k$$

where x_j is the probability of being in condition state j at the beginning of the year; y_k is the probability of being in condition state k at the end of the year; and p_{jk} is the transition probability from j to k. This computation can be repeated to extend the forecast for additional years until the failed percentage reaches 50%. (Table 4-28 showed an example.)

5.2.1.3 Weibull Model

For a Weibull survival probability model, equivalent age is easily calculated from the inverse of the Weibull prediction formula. The Weibull curve has the following functional form:

$$y_{1g} = \exp\left(-1.0 \times \left(g/\alpha\right)^{\beta}\right)$$

where y_{1g} is the probability of the not-failed state at age g, if no intervening maintenance action is taken between year 0 and year g; β is the shaping parameter; and α is the scaling parameter, calculated as

$$\alpha = \frac{t}{\left(\ln 2\right)^{1/\beta}}$$

where t is the median life expectancy from the Markov model. This is calculated in the same way as described earlier in this chapter. The inverse of the Weibull formula is

$$g' = \alpha \times 10\char`\^\left(\frac{\log\left(-\ln\left(y_1\right)\right)}{\beta}\right)$$

This yields the age that is equivalent to the given non-failed fraction y_1.

5.2.1.4 Convert a Markov Model to a Weibull Model

Another way to calculate equivalent age for a Markov model is to develop a function to convert a condition state description of condition into a condition index representative of the equivalent point in its life span. Then the inverse Weibull formula, as presented in the preceding section, can be used to estimate the equivalent age based on the condition index at any point in time.

This function would be applied to the known asset condition to simplify its representation and would also be applied to conditions forecasted by the deterioration model. In this way, the transition probability matrix is presented in the form of a linear depiction of the change in median condition over time, and any known condition state representation can be converted to a point on that line, making it possible once again to read off the equivalent age directly. The steps to do this are as follows (Table 5-3):

1. Develop the Markovian transition probability matrix using the tools described earlier in this chapter. Either the linear regression method or the one-step method will work.

2. Convert each row of the matrix to median transition time, using the familiar formula

$$t_j = \frac{\log(0.5)}{\log(p_{jj})}$$

where p_{jj} is the probability of remaining in the same condition state from one year to the next, and t_j is the median amount of time spent in condition state j before moving on to condition state $j + 1$.

Table 5-3. Model to estimate equivalent age from a Markov model.

Step 1: Transition probabilities (One-Step Method, from previous example)

Condition state probabilities	1	2	3	4
Stay in same state	88.5	84.2	74.7	100
Deteriorate one step	11.5	15.8	25.3	0.0

Step 2: Median transition time

	1	2	3	4	Sum
Median transition time	5.66	4.02	2.38		12.1

$$t_j = \frac{\log(0.5)}{\log(p_{jj})}$$

t is median transition time
p is same-state transition probability

Step 3: Condition state weights

	1	2	3	4
State weight	1.00	0.53	0.20	0.00

$$w_j = \frac{1}{\sum_j t_j}\sum_{k=j}^{N} t_k$$

w is weight given to each state
t is median transition time
N is the total number of condition states

Step 4: Condition index forecast / **Step 5: Equiv age model**

$$CI = \sum_j w_j x_j$$

Year	Condition state probabilities 1	2	3	4	Cond index	Predict age	Square deviation	Log likelihood
0	100	0.0	0.0	0.0	100.0	0.00	0.0000	1.2688
1	88.5	11.5	0.0	0.0	94.6	1.26	0.0694	-1.4902
2	78.3	19.9	1.8	0.0	89.2	2.27	0.0731	-1.6377
3	69.3	25.8	4.5	0.5	83.8	3.23	0.0538	-0.8676
4	61.3	29.7	7.4	1.6	78.5	4.18	0.0327	-0.0288
5	54.2	32.0	10.3	3.5	73.2	5.13	0.0168	0.6024
6	48.0	33.2	12.7	6.1	68.1	6.08	0.0070	0.9906
7	42.4	33.5	14.8	9.3	63.1	7.05	0.0021	1.1868
8	37.5	33.1	16.3	13.0	58.3	8.02	0.0002	1.2594
9	33.2	32.2	17.5	17.2	53.7	8.99	0.0000	1.2670
10	29.4	30.9	18.1	21.6	49.4	9.98	0.0005	1.2509
11	26.0	29.4	18.4	26.1	45.3	10.97	0.0009	1.2349
12	23.0	27.8	18.4	30.8	41.4	11.97	0.0010	1.2294
13	20.4	26.0	18.2	35.5	37.8	12.97	0.0008	1.2357
14	18.0	24.2	17.7	40.0	34.4	13.98	0.0005	1.2491
15	15.9	22.5	17.1	44.5	31.2	14.99	0.0002	1.2627
16	14.1	20.8	16.3	48.8	28.3	16.00	0.0000	1.2688
17	12.5	19.1	15.5	52.9	25.7	17.01	0.0002	1.2607
18	11.0	17.5	14.6	56.9	23.2	18.03	0.0009	1.2336
19	9.8	16.0	13.7	60.5	21.0	19.05	0.0021	1.1847
20	8.6	14.6	12.8	64.0	18.9	20.06	0.0039	1.1135
21	7.6	13.3	11.8	67.2	17.0	21.08	0.0062	1.0214
22	6.8	12.1	11.0	70.2	15.3	22.09	0.0090	0.9119
23	6.0	10.9	10.1	73.0	13.8	23.11	0.0121	0.7897
24	5.3	9.9	9.3	75.5	12.4	24.12	0.0153	0.6606
25	4.7	8.9	8.5	77.9	11.1	25.14	0.0186	0.5311

Coefficient	Value
Index at life expectancy	
Life expect	16.00
Predicted life	16.00
Equiv age parameters	
Scaling (alpha)	13.25
Shaping (beta)	1.2297
Std deviation	0.1122
Sum LogLike	19.989

$$g' = \alpha \times 10\text{^}\left(\frac{\log(-\ln(y_1))}{\beta}\right)$$

g is equivalent age
y is condition index

3. Each condition state will be allocated a portion of the asset's life, in proportion to its transition time. So compute the weight of each condition state as

$$w_j = \frac{1}{\sum_j t_j} \sum_{k=j}^{N} t_k$$

This formula assumes that 1 is the best state and N is the worst. The weight given to the best state is 1.0, and the weight given to the worst state is 0, with all other states having weights in between.

4. Compute the equivalent condition index from the condition state distribution using the formula

$$CI = \sum_j w_j x_j$$

The forecasts from the transition probability matrix are run through this computation to generate a deterministic time series of condition index, starting at 1.0 for an asset in perfect condition and approaching zero as the asset ages long past its life expectancy. A Weibull model can be developed from this time series, using maximum likelihood estimation constrained so that the equivalent age equals the actual age at the asset life expectancy. Figure 5-9, which is based on the results of Table 5-3, shows that the Weibull model is an excellent fit to data generated in this way. The method is exactly the same as for the calculation of survival probability, but in this case it is used instead on a condition index. Once this model is developed, any condition state vector for the asset can be simplified to an equivalent age, even if the asset has already passed its life expectancy.

5.2.2 Life Extension Benefits of Actions

Typically the effect of repair and rehabilitation actions is expressed as an improvement in condition. Once the improved condition is forecast, the methods in the preceding section can be used to calculate equivalent age, before and after the action. The difference in age is one way of expressing the benefit of the action (Figure 5-10).

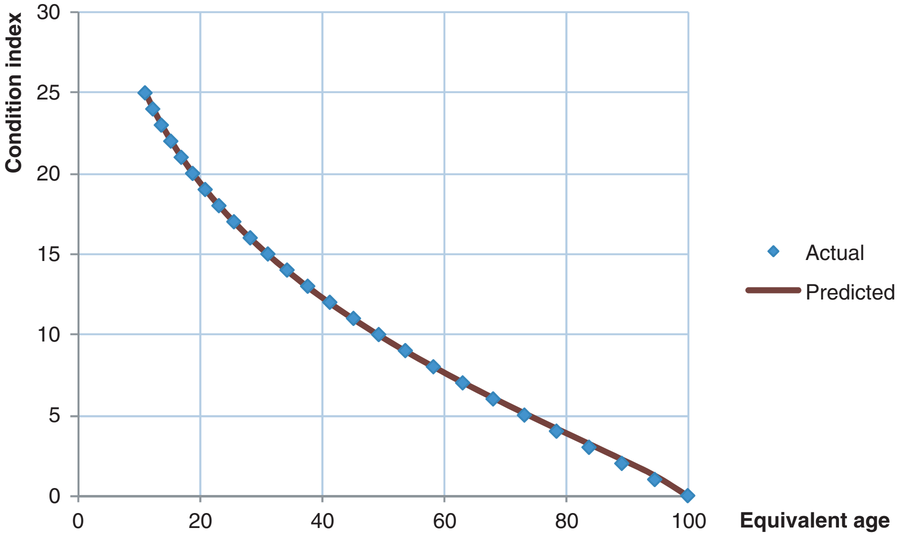


Figure 5-9. Condition index versus equivalent age from Table 5-3.

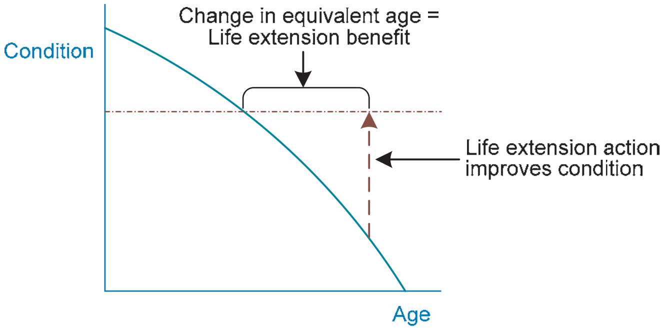


Figure 5-10. Converting condition improvement to life extension benefit.

5.2.3 Remaining Life

One of the most obvious ways to compute remaining asset life is to subtract the actual age of an asset from its life expectancy. This method is valid if no life extension actions have been performed.

However, if an asset has been repaired, or if its maintenance history is unknown, then it is more accurate to use a condition-based approach, taking advantage of the deterioration and equivalent age models presented in this chapter. Assuming that the asset's life is not limited by impending functional needs or changes in standards, the current condition of the asset can be converted to its equivalent age, essentially finding its most likely place on the deterioration curve. This equivalent age is then subtracted from life expectancy to estimate remaining asset life (Figure 5-11).

The equivalent age method works regardless of what preservation work may have been performed in the past, even if the past work is unknown. However, one limitation is that it assumes that no future work will be done. For many applications, this assumption is desirable. However, if the goal is to estimate when the asset will actually be replaced, then the possibility of future life extension actions must be considered.

Models of repair feasibility and effectiveness are beyond the scope of this guide, but such models do exist and are widely used for pavements and bridges and could be developed for other assets, based on agency data and experience. If a life extension action is found to be feasible and if its condition benefit can be estimated, then the equivalent age method provides a direct estimate of the added life, as shown in Figure 5-12.

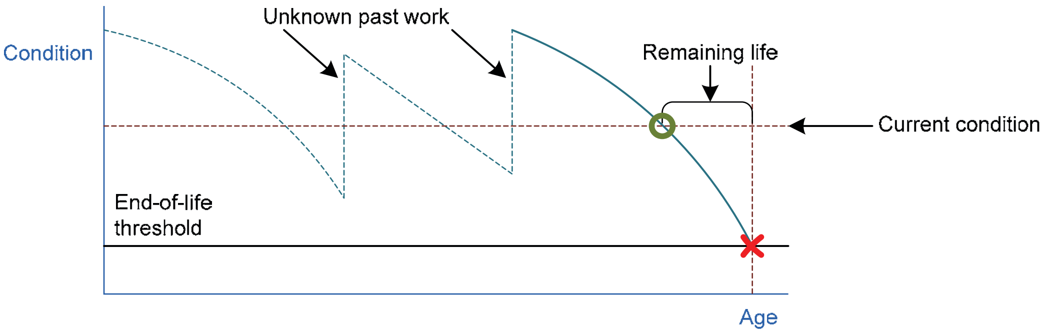


Figure 5-11. Remaining asset life from current condition.

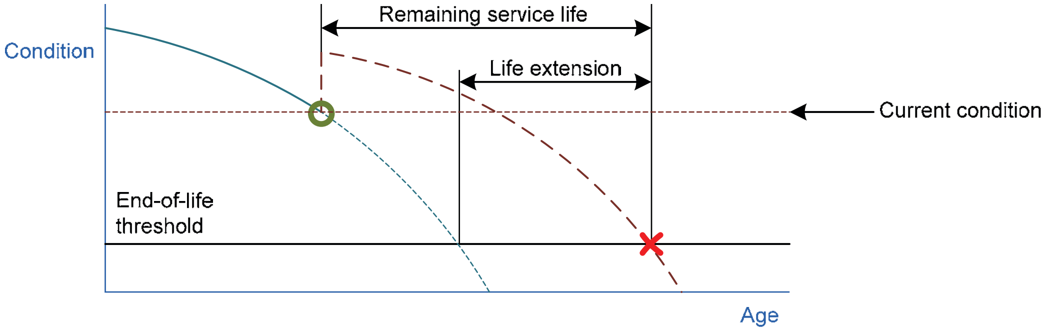


Figure 5-12. Remaining life with future extension.

5.2.4 Lifecycle Cost Models

Adding lifecycle cost to life expectancy and deterioration models opens the door to a wealth of useful applications to support transportation asset management decision-making. Among the possible applications are the comparison of design and life extension alternatives, optimizing replacement intervals, optimizing preventive maintenance, evaluating new maintenance materials and techniques, optimizing corridor planning, and responding effectively to funding constraints. Lifecycle cost models are key ingredients in asset management systems, such as for pavements and bridges; but the models are often simple enough that they can be implemented as Microsoft Excel spreadsheets.

5.2.4.1 Time Value of Money

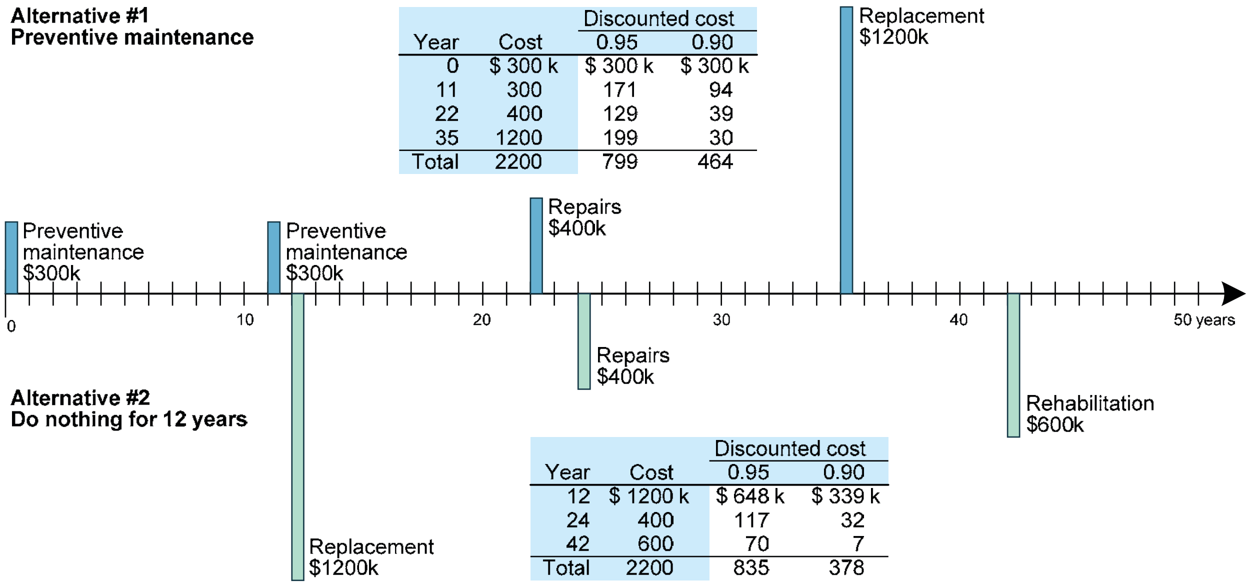
One of the key concepts of lifecycle cost analysis is the time value of money. In economic decision-making, people value near-term revenue and near-term costs more highly than money that changes hands years in the future. People are willing to pay interest in order to have access to money today that they might not otherwise see for many years. Agencies issue bonds and pay interest on those bonds. Future needs for money are less certain.

Another key aspect of lifecycle cost is the timing of the decisionmaker's cost and benefit horizon, and the timing of asset life expectancy. State Transportation Improvement Programs (STIPs) and budgets have defined time horizons, where accountability for costs and outputs is increased. Political terms in office are also limited. These factors tend to push costs into the future while concerns for outcomes are more immediate.

Figure 5-13 depicts a typical set of cost streams for a bridge, showing how the choice of a discount factor affects the calculation of lifecycle cost. The top and bottom of the figure are two different lifecycle activity profiles (Hawk 2003), sets of agency actions timed according to deterioration, action effectiveness, and cost. Both profiles are feasible for the bridge, each having its own strengths and weaknesses.

Alternative 1 features relatively frequent, but small, preventive maintenance activities. With a discount factor of 0.95, the difference in value between future costs and current costs is small, so there is more willingness to spend in the near term to gain long-term benefits, such as extension of the life of the structure. As a result, Alternative 1 has lower overall lifecycle cost at a discount factor of 0.95. At the lower discount factor of 0.90, on the other hand, Alternative 2 becomes more attractive.

Figure 5-14 shows another example of lifecycle cost analysis, for replacement of traffic signal lamps. With the shorter time frame measured in weeks, discounting of future costs plays less of a role than for bridges. Yet, the economic considerations are substantial in comparing policies.



Year	Cost	Discounted cost 0.95	Discounted cost 0.90
0	$ 300 k	$ 300 k	$ 300 k
11	300	171	94
22	400	129	39
35	1200	199	30
Total	2200	799	464

Year	Cost	Discounted cost 0.95	Discounted cost 0.90
12	$ 1200 k	$ 648 k	$ 339 k
24	400	117	32
42	600	70	7
Total	2200	835	378

Figure 5-13. Example of bridge lifecycle cost alternatives.

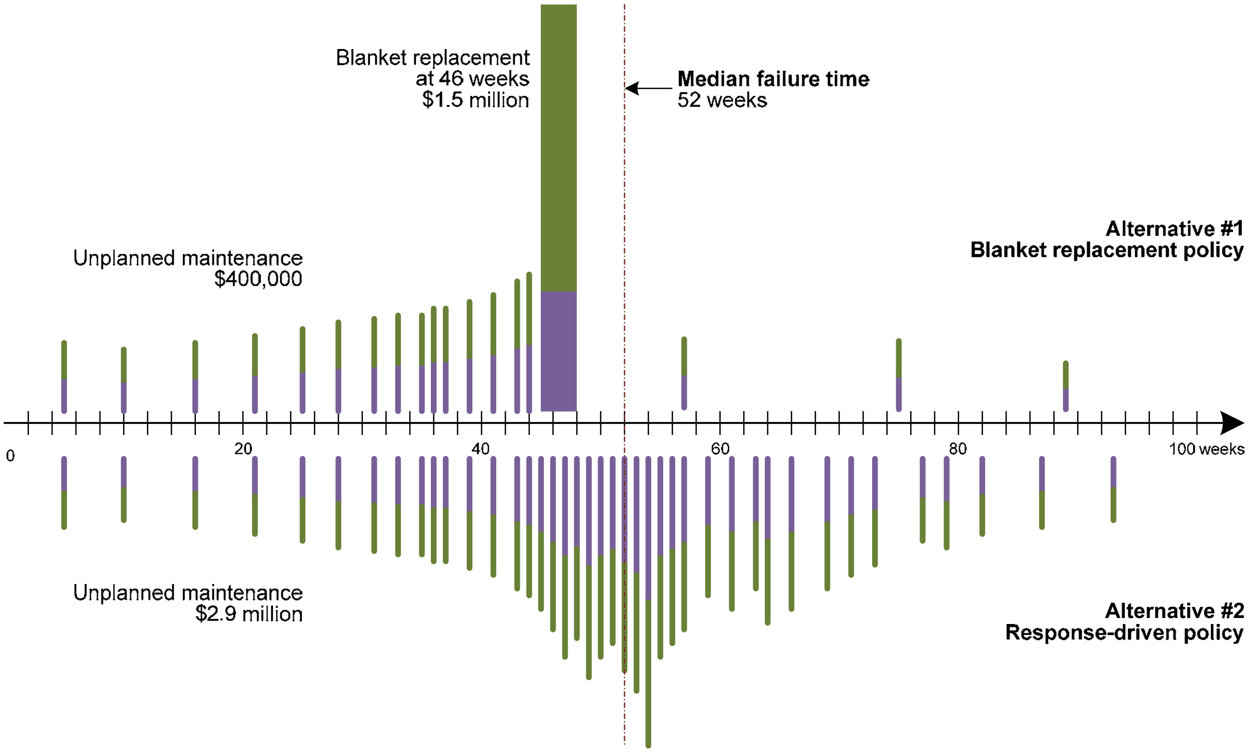


Figure 5-14. Example of cost streams for traffic signal lamp replacement.

The blanket replacement policy saves one million dollars by reducing the mobilization and traffic control costs of unplanned traffic signal failures. The optimal time for replacement depends on the width of the probability distribution, which is the level of uncertainty in the median failure time. If the timing of the blanket replacement policy were set too far to the left or the right, it could end up being more expensive than the response-driven policy.

5.2.4.2 Common Methods

The mathematical formulas for computing lifecycle cost are well known in asset management applications. The discount factor is calculated from

$$d = \frac{1}{1+i}$$

where i is the real discount rate. Usually agencies set the discount rate for asset management policy to be consistent with the cost of public-sector bond financing. Although inflation can either be included or not included, it is usually much simpler to omit inflation from all lifecycle cost computations. Most published reports about lifecycle cost omit inflation, which is generally the reader's expectation. The missing inflation, of course, must be added back as a part of discussions of future nominal budgets. The discount rate should be consistent among all asset management applications.

The present value of a one-time future cost or benefit is calculated from

$$PV = d^n \times FV$$

where n is the time interval between the base year of the analysis (usually the current year or the first year of a program), and the year when the cost or benefit is to be realized; and FV is the future value of the cost or benefit estimate for the time that it is realized (again omitting inflation).

If a uniform annual series of costs or benefits is expected for an indefinite period of time into the future, this is called a perpetuity. The present value of a perpetuity is

$$PV = \frac{FV}{i}$$

where FV is the annual payment, starting 1 year from the present.

If the future uniform series is not annual (perhaps it is once every 2 years), it is simplest to change the discount rate to match the desired time interval. First calculate the equivalent discount factor, then apply the appropriate exponent for the desired time interval, then convert this back to a discount rate. For example, if $i = 5\%$, then $d = 0.9524$. For a 42-month (3.5-year) interval, such as the replacement interval for a certain type of street lamp, the full discount is $0.9524^{3.5} = 0.843$. The corresponding discount rate $i = (1\text{-}0.843)/0.843 = 18.624\%$.

For a transportation facility with initial investment, P; compounded amount of all cash flows within a replacement lifecycle, R, and length of replacement lifecycle, N years, the present worth of all payments in perpetuity is given by, $PW_\infty = P + R/((1+i)^N - 1)$. However, in cases where the facility already exists, P is a sunk cost, and the present worth is $PW_\infty = R/((1+i)^N - 1)$.

If a uniform annual stream of costs or benefits has a definite end, then the present value is

$$PV = FV \frac{1-(1+i)^{-n}}{i}$$

Here *FV* is again the amount of the future recurring payment, starting 1 year from the present. If the stream of cash flows corresponds to the life span of an asset, then *n* is typically the median life expectancy of the asset. However, there are applications where *n* should be some other value, such as a proposed blanket replacement date that might be earlier than the life expectancy. If the uncertainty in the life expectancy is large, or if its variability is asymmetrical (e.g., minimally spread before the median, but widely spread afterward), then it may be more accurate to represent the cash flows individually rather than as a uniform stream.

5.2.4.3 Comparing Alternatives Using Net Present Value

Net present value is a term used to describe the sum of all relevant costs and benefits at stake in a decision, with each cash flow discounted to the same year, usually the year of the decision. Lifecycle cost is usually understood to be a type of net present value.

It is important to be clear on the definitions of what is and is not included in the computation. In lifecycle cost analysis, generally, two or more specific alternatives are compared, the decision being to select one or the other. One of the decisions might be "do nothing" or "do what we are doing now" or "base case."

If a particular cost has exactly the same amount and timing in both alternatives, then it must either be included in both or excluded from both. If the amount or timing differ, then both should be included. If one alternative includes initial costs and ongoing routine maintenance costs, then the other alternative must also include these costs. Similarly, it is important to include user costs in a consistent manner, ensuring that the same types of costs are included or excluded from both alternatives.

All costs and benefits that are significant in selecting between the alternatives should be included. Occasionally there can be confusion about whether a cash flow is a cost or a benefit. Whenever possible, it is simpler and less confusing if all cash flows are treated as costs. For user costs, externalities, and costs of other agencies, it is important to be clear and consistent about who is paying the costs. For example, if Public Safety Department costs are included in one alternative, they should be included in both. Sometimes there are large distinctions among alternatives in terms of federal, local, or private cost participation.

It is generally necessary for the costs of each alternative to be considered over the same time frame. It is desirable for this time frame to be long enough that all differences between the alternatives can be accounted for. However, for long-lived assets this may be unrealistic. In that case, it is important to consistently account for the long-term residual costs beyond the end of the analysis period. Common ways of doing this include

- Computing a salvage value, a hypothetical revenue amount for selling the asset at the end of the period, considering the condition and performance of the asset forecast at that time.
- Computing a lump-sum long-term cost representing all future costs beyond the analysis period, sensitive to condition and performance at the end of the period.
- Computing the repair cost that would be required at the end of the period to restore the asset to near-new condition (or at least to the same condition) under both alternatives.
- Computing lifecycle costs over a long enough period that discounting and/or uncertainty reduces any differences in subsequent costs to irrelevance.
- Structuring the analysis as a perpetuity by including recurrent replacement and lifecycle costs extending the total life of the asset and its successors into the indefinite future.

Lifecycle cost alternatives are usually compared by selecting the one with the lowest net present cost or highest net present value. However, in asset management often there are relevant costs and benefits that are non-economic or that are experienced by customers and stakeholders rather than by the agency. For these cases, there are more general methods of multi-objective analysis that are appropriate (Patidar et al. 2007).

5.2.4.4 Comparing Alternatives Using Equivalent Uniform Annual Cost

For certain purposes and certain audiences, it is useful to compare alternatives by converting net present value to equivalent uniform annual cost (EUAC). This calculation is just the inverse of the annuity formula described previously:

$$EUAC = NPV \frac{i}{1-(1+i)^{-n}}$$

where NPV is the net present value computed as described previously. This method is especially useful when comparing an agency investment against an alternative where the same service is provided by a contractor, where the contractor finances equipment acquisitions and charges the agency an annual amount.

EUAC also is used in presenting investment amounts or lifecycle cost analysis to the public, where it might be converted to a cost per person. For example, a proposed sign washing program might be presented as costing 10 cents per taxpayer per year, but which is saving 15 cents due to longer asset life and lower replacement costs. This makes the argument easier to understand for people who do not have an intuitive feel for the much larger amounts that appear in budget documents.

Comparisons among alternatives using EUAC should always produce exactly the same results as comparisons using NPV. However, it is very helpful to have tools such as EUAC readily available to help make economic arguments more accessible to the layperson.

5.2.4.5 Comparing Alternatives Using Internal Rate of Return

For certain applications, an alternative to NPV is internal rate of return. The rate of return computation still requires computing the NPV of each alternative so in general it uses the same models and principles. The main difference is that the discount rate is considered uncertain and variable. To compute the internal rate of return, the analyst iteratively tries out a range of possible discount rates until finding one that equalizes the NPV between the alternatives. (This process is easily automated in a Microsoft Excel spreadsheet model.) If this rate of return is far from market rates, then one alternative is considered to be far superior to the other. If the discount rate is close to market rates, then the economic analysis might be considered inconclusive.

Internal rate of return is useful when the agency is considering creative financing alternatives for a project, where the cost of money may be variable or may be divided between the public and private sectors. It is also useful for communicating with certain audiences that routinely work with discount rates. Sometimes the technique is useful for political decision-making when the difference in NPV among alternatives is small, but it might not be clear to the audience just how small it is. If the rate of return is within a range of familiar market rates, this might provide cover for pursuing an alternative that has greater political appeal in preference to one that strictly minimizes lifecycle costs.

5.2.4.6 Benefit/Cost Ratio

There are many applications where it is necessary to compare alternative uses of a fixed amount of money, for example, in setting priorities. For this purpose, benefit/cost analysis is useful. To construct a benefit/cost analysis of asset investments, it is necessary to identify a set of alternatives for each asset and develop a criterion for ordering the alternatives. Usually it is assumed that the assets are independent of each other and that any combination of them can be implemented, subject to a funding constraint.

In the simplest and most common case, there are two alternatives: do-nothing and do-something. The do-nothing alternative may have zero cost or may include routine maintenance and operational costs. In any event, it has a lower cost than do-something. If the decisionmaker is considering spending the additional money needed for the do-something alternative, then there must be a benefit for this expenditure.

Often the benefit is calculated by comparing lifecycle costs by subtracting the lifecycle cost of do-something from the lifecycle cost of do-nothing. Lifecycle cost includes the initial cost and is often computed using the NPV method. If this difference in lifecycle costs is positive, then the expenditure is attractive because it saves money in the long term. When there are multiple objectives such as condition, risk, and/or safety to be considered, and not just lifecycle cost, then a utility framework might be used (Patidar et al. 2007) in order to calculate the benefit.

A set of investment alternatives is prioritized by sorting the alternatives by the ratio of benefit to cost. When funding is limited, the alternatives with the highest benefit/cost are selected.

If a particular asset has more than just the two investment alternatives, a variation on this method is used. The alternatives on the one asset are sorted in order by cost and evaluated by comparing each alternative with the next-less-expensive alternative. The sorting criterion is then the incremental benefit divided by incremental cost, which is called the incremental benefit/cost ratio.

5.2.4.7 Agency Cost and User Cost

An important issue in lifecycle cost analysis is the ratio of the values of agency cost to that of user cost. Agency costs are the costs incurred by the transportation facility or service provider and such costs can be incurred during construction, preventive maintenance, rehabilitation, or reconstruction stages and also during normal operation phases. A highway agency responsible for construction and maintenance of highway assets incurs costs including initial costs associated with feasibility studies, engineering design, construction, operation of the facility, maintenance and rehabilitation, and disposal costs. In lifecycle cost analysis for assets such as pavements, preliminary costs such as feasibility and engineering studies are excluded because those are typically common among all alternatives considered.

User costs are costs incurred by the highway users over the life of the project and may depend on highway improvements and associated maintenance and rehabilitation strategies over the analysis period. User costs may form a substantial part of total lifecycle costs and can often be the major determining factor in the analysis. User costs can be either work-zone user costs or non-work-zone user costs and components of user costs include vehicle operation cost, travel time cost, safety cost, and the costs from noise and water and air pollution.

Agencies sometimes assign a weight less than 1.0 to user costs to reduce their effect on the lifecycle cost analysis. This may be reflective of actual agency decisions that do not give full weight to costs borne by road users and outside the agency's budget.

5.3 Example Applications

With the building blocks discussed in this chapter, it becomes possible to create various useful asset management applications. As the earlier chapters demonstrated, each agency will have its own needs so the applications may differ substantially from one to another. The process of discovering needs and incorporating them and gaining buy-in, interest, and demand may be more important than the sophistication of the applications themselves.

The examples in this section are not intended to be full-scale, implementable management systems, bur relatively simple and transparent demonstrations of life expectancy analysis on small but realistic types of problems. These examples can be a source of ideas and clarity for agencies wishing to develop their own decision support tools.

5.3.1 Routine Preventive Maintenance

A common maintenance planning issue is the question of whether to start routine programs of crew activities that might have life extension benefits. Common examples are sealing of pavement cracks; washing of bridges, signs, pavements, and guiderails; spot painting; concrete patching; and cleaning of equipment enclosures. Here is an example of comparing a preventive maintenance scenario with the do-nothing scenario.

Through the application of preventive maintenance, the two scenarios will have different service lives. For comparing asset alternatives that have different service lives, there are at least three approaches:

- For each alternative, convert all costs and benefits into EUAC,
- For each alternative, compute lifecycle cost over an asset life that is a lowest common denominator of the separate life expectancy estimates, or
- For each alternative, find the present worth of periodic payments to perpetuity.

In this example, let us make a comparison of pavement management strategies using the EUAC approach comparing the two strategies in Table 5-4. For the routine preventive maintenance strategy, assume crack sealing is performed every 4 years at \$400 per lane-mile, resulting in a life extension of 4 years; for the do-nothing option, assume only reconstruction is performed at a cost of \$30k for both alternatives. Assume a discount rate of 4%.

The EUAC of the two alternatives can be compared as follows:

$$PV_{Routine\ Preventive\ Maintenance} = \$400\left[\frac{1}{(1+0.04)^{4}} + \frac{1}{(1+0.04)^{8}} + \cdots \frac{1}{(1+0.04)^{20}}\right] + \$30,000\left[\frac{1}{(1+0.04)^{24}}\right]$$

$$= \$9,083/\text{lane-mile}$$

$$EUAC_{Routine\ Preventive\ Maintenance} = \$9,083\left[\frac{0.04(1+0.04)^{24}}{(1+0.04)^{24}-1}\right] = \$596/\text{lane-mile}$$

$$EUAC_{Do\text{-}Nothing} = \$30,000\left[\frac{0.04}{(1+0.04)^{20}-1}\right] = \$768/\text{lane-mile}$$

Table 5-4. Example lifecycle activity profiles to be compared.

Year	Cost per lane-mile by strategy	
	Routine Preventive Maintenance	Do-Nothing
1 ...		
4 ...	\$400	
8 ...	\$400	
12 ...	\$400	
16 ...	\$400	
20 ...	\$400	\$30,000
24	\$30,000	

With these assumptions, the agency could reduce annual costs by $172 per lane-mile if routine preventive maintenance is completed.

5.3.2 Optimal Replacement Interval

Certain types of assets may have various asset life alternatives, depending on different strategies for maintenance and life extension. The optimal asset life would be the lifecycle activity profile that can be sustained at minimum lifecycle cost. Here is an example of comparing several alternative profiles.

After several decades of service, a railway bridge is slated for reconstruction. The estimated asset life of the structure is 50 years. The reconstruction cost is $600,000. During its replacement cycle, the bridge will require two rehabilitation events, each costing $200,000, at the 25th and 40th years, and the average annual cost of maintenance is $5,000. At the end of the replacement cycle, the bridge will again be reconstructed and the entire cycle is assumed to recur to perpetuity. Assuming a discount rate of 5%, the present worth of all bridge agency costs in perpetuity was calculated to be $753.15k.

The agency would like to consider a range of potential life extension strategies to determine if they are economical. As a second alternative, it is found that the asset life of the bridge can be extended to 60 years with rehabilitation in the 25th and 45th years, with only minor degradation in the level of service. By adding a third rehabilitation cycle, the agency finds that it can further extend the asset life to 70 or 80 years. Table 5-5 shows all the alternatives.

In this example, Option 3 gives the lowest lifecycle cost. In Figure 5-15, the present worth values of the different estimates of lifecycle cost are plotted against the different estimates of asset life of the bridge, using a smoothed trend line. This suggests that the optimum replacement cycle is about 64 years. Moreover, the shape of the curve suggests that the present worth of the cost declines rapidly from 50 years to 60 years; but between 60 and 70 years, the curve is relatively flat, indicating that the asset manager has some flexibility in deciding on the replacement cycle in this range.

Table 5-5. Example system replacement interval optimization.

	Option 1	Option 2	Option 3	Option 4
Replacement Cost	600	600	600	600
Rehabilitation Cost	200	200	200	200
Annual Maintenance Cost	5	5	5	5
Estimated Asset Life	50	60	70	80
Rehabilitation Years	25	25	25	20
	40	45	45	40
			55	60
Discount Rate	0.05	0.05	0.05	0.05
Compounded Lifecycle Cost	7883.51	12726.51	21145.92	35411.36
Present Worth at Perpetuity	753.15	719.86	718.60	729.21

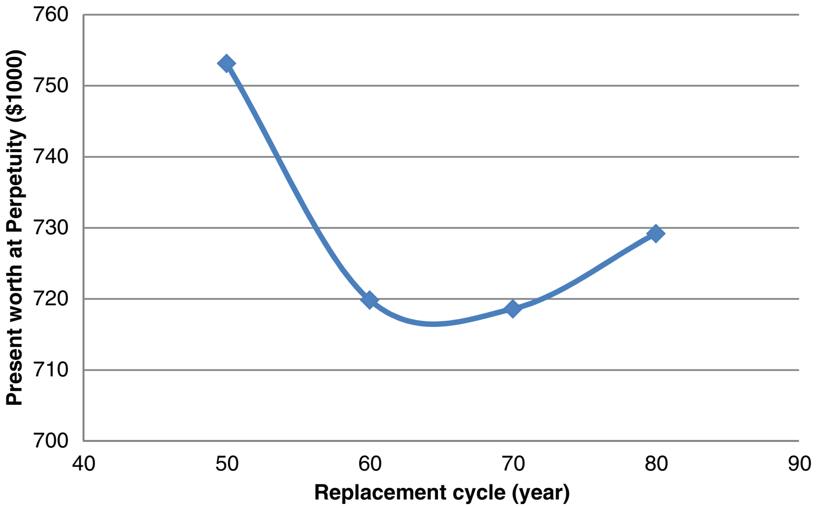


Figure 5-15. Smoothed graph of the alternatives in Table 5-5.

5.3.3 Comparing and Optimizing Design Alternatives

It is a very common need to compare two products or methods that have different costs, different life expectancies, and different life extension possibilities. Here is an example, considering the case of deciding to apply a coating to a pipe culvert.

Assume an engineer must decide whether to replace an existing pipe culvert with a coated or a non-coated pipe culvert, provided that a coated culvert is expected to survive 50 years with compounded amount of all cash flows within the replacement lifecycle to be $1200 while a non-coated culvert is expected to survive 40 years and the compounded amount of all cash flows within the replacement lifecycle is $1000.

As discussed in Section 5.3.1, three possible ways of making this comparison would be an annual cost basis using EUAC, a least common multiple analysis period consisting of multiple replacement cycles, or a perpetuity of replacement cycles. For this example, a perpetuity is assumed, with a 4% discount rate. The present values of the two options, computed as perpetuities, then are

$$PV_{no\ coating}^{\infty} = \$1000 \times \left(\frac{1}{(1+0.04)^{40} - 1} \right) = \$263.1$$

$$PV_{coating}^{\infty} = \$1200 \times \left(\frac{1}{(1+0.04)^{50} - 1} \right) = \$196.5$$

Therefore, the coated design option is preferred.

5.3.4 Comparing and Optimizing Life Extension Alternatives

Similar to the previous example is the need to compare two or more life extension alternatives with different costs and effectiveness. Consider the set of alternatives presented in Table 5-6, for a bridge having a do-nothing asset life of 50 years, a replacement cost of $500k, and an interest rate of 4%.

In a bridge management system, these types of strategies are typically compared on a NPV basis, and more than one of them may be selected. For the current example, EUAC is used as the selection criterion.

Table 5-6. Example bridge life extension alternatives.

Activity	Frequency	Life Extension of Activity at Applied Frequency	Activity Cost
Deck overlay	Every 20 years	7	\$15k
Deck patching	Every year	3	\$500
Joint replacement	Every year	2	\$300
Deck overlay & joint replacement	Overlay every 20 years & joint replacement every year	9	\$15k for overlay and \$100 for joint replacement
Deck patching & joint replacement	Every year	5	\$700
Deck rehabilitation	Once at year 35	30	\$200k

EUAC of Deck Overlay

$$= \left[\$15\text{k} * \left(\frac{1}{(1+0.04)^{20}} + \frac{1}{(1+0.04)^{40}} \right) + \$500\text{k} * \left(\frac{1}{(1+0.04)^{50+7}} \right) \right] * \frac{0.04(1+0.04)^{50+7}}{(1+0.04)^{50+7} - 1}$$

$$= \$2.84\text{k}$$

$$\text{EUAC of Deck Patching} = \$500 + \left[\$500\text{k} * \left(\frac{1}{(1+0.04)^{50+3}} \right) \right] * \frac{0.04(1+0.04)^{50+3}}{(1+0.04)^{50+3} - 1} = \$3.36\text{k}$$

$$\text{EUAC of Joint Replacement} = \$300 + \left[\$500\text{k} * \left(\frac{1}{(1+0.04)^{50+2}} \right) \right] * \frac{0.04(1+0.04)^{50+2}}{(1+0.04)^{50+2} - 1} = \$3.29\text{k}$$

EUAC of Deck Overlay and Joint Replacement

$$= \$100 + \left[\$15\text{k} * \left(\frac{1}{(1+0.04)^{20}} + \frac{1}{(1+0.04)^{40}} \right) + \$500\text{k} * \left(\frac{1}{(1+0.04)^{50+9}} \right) \right] * \frac{0.04(1+0.04)^{50+9}}{(1+0.04)^{50+9} - 1}$$

$$= \$2.74\text{k}$$

EUAC of Deck Patching and Joint Replacement

$$= \$700 + \left[\$500\text{k} * \left(\frac{1}{(1+0.04)^{50+5}} \right) \right] * \frac{0.04(1+0.04)^{50+5}}{(1+0.04)^{50+5} - 1} = \$3.32\text{k}$$

EUAC of Deck Rehabilitation

$$= \left[\$200\text{k} * \left(\frac{1}{(1+0.04)^{35}} \right) + \$500\text{k} * \left(\frac{1}{(1+0.04)^{50+30}} \right) \right] * \frac{0.04(1+0.04)^{50+30}}{(1+0.04)^{50+30} - 1}$$

$$= \$3.32\text{k}$$

$$\text{EUAC of Do Nothing} = \$500\text{k} * \left(\frac{0.04}{(1+0.04)^{50} - 1} \right) = \$3.28\text{k}$$

From this array of activity options, the improvement strategy that minimizes cost under these assumptions is annual deck overlay and joint replacement. It can also be seen that the life extensions from patching, joint replacement, and rehabilitation under these assumptions are not cost-effective.

5.3.5 Pricing Design and Preservation Alternatives

Many agencies invest in research and development programs so as to produce practical, cost-effective designs and materials. The primary concern with innovations, however, relates to reliability, life extension benefits, and cost of application. To facilitate decisions on whether to apply a new design, agencies often assess break-even points (i.e., the levels at which alternative designs become less costly than the traditional design).

Example. For a bridge planned for construction, an agency wishes to assess the feasibility of using solid stainless steel reinforcement bars in place of traditional carbon steel. The bridge length and total deck width (ft) are 148.66 and 49.33, respectively; traffic volume is 8,527 AADT; weight of deck reinforcement is 62,963 lbs; and during the construction, rehabilitation, and deck replacements, work-zone traffic is diverted to a 1.3-mile 30-mph detour. If the lives of two bridges are 75 years and 100 years, respectively, with the activity profiles shown in Figure 5-16A, at what price is the stainless steel alternative preferred? The project durations for initial construction, deck replacement, and deck rehabilitation are 120, 60, and 21, respectively.

Values of other analysis variables are as follows: discount rate = 4%; Vehicle occupancy = 1.8; minimum hourly wage = \$13.43; average fuel economy = 23 mpg; cost of fuel = \$3.75\$/gal; traditional carbon steel price = 1.15\$/lb; carbon steel service life = 40 yrs; stainless steel service life = 100 yrs.

Results. The result of the analysis is shown in Figure 5-16B. This depicts the values of the ratio of the lifecycle cost of the stainless steel option relative to the traditional steel option, at various ratios of the price of stainless steel relative to traditional steel. The differences in the lifecycle costs of stainless and traditional steel arise from their different lifecycle profiles which in turn result from the differences in the deck life (stainless steel decks have been found to have greater longevity (Cope 2009). Figure 5-16B shows that the stainless steel alternative is the superior alternative as long as the stainless steel price is less than 8.7 times the price of traditional steel. This is referred to as the price threshold ratio (PRT) for stainless steel desirability. The higher the PRT, the more favorable is the use of stainless steel. Higher values of the discount rate, vehicle occupancy, minimum hourly wage, fuel cost, and stainless steel service life, and lower values of average fuel economy would cause the Price Ratio function to shift to the right and thus, a higher PRT and consequently, an expanded range of cost-effectiveness for the stainless steel option.

5.3.6 Synchronizing Replacements

Along a busy highway corridor, maintenance interventions can often be costly and disruptive. In some places, there's never a good time to close a lane. When an agency has a good set of alternatives for design and life extension, it is useful to see what combination of products and techniques will minimize the required number of traffic control installations.

Traditional Steel

- Year 0: Initial Construction
- Year 20: Rehabilitation (deck overlay)
- Year 40: Deck Replacement
- Year 60: Rehabilitation (deck overlay)
- Year 75: End of Life

Stainless Steel

- Year 0: Initial Construction
- Year 50: Rehabilitation (deck overlay)
- Year 75: Rehabilitation (deck overlay)
- Year 100: End of Life

Figure 5-16A. Example activity profiles for carbon steel and stainless steel options *(Cope 2009).*

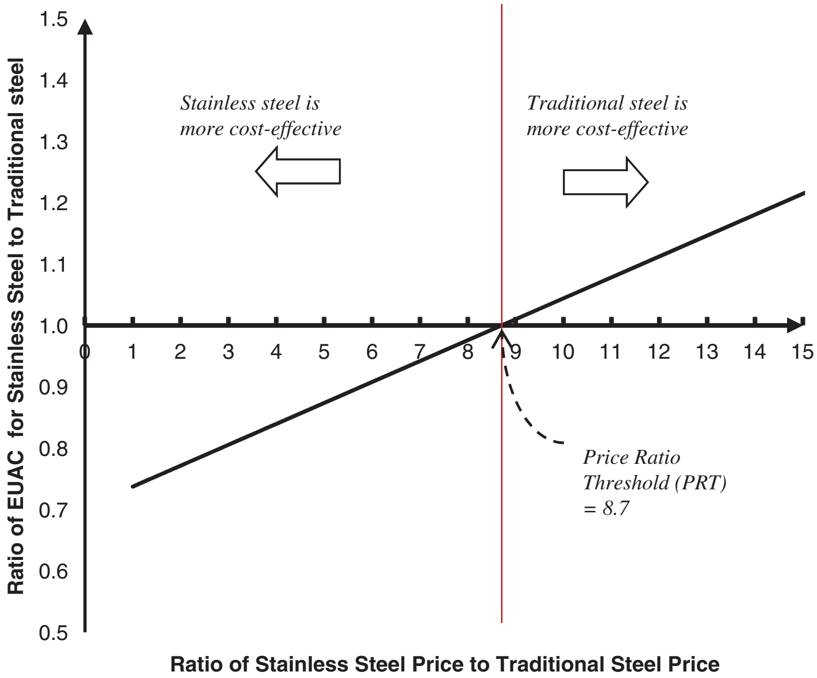


Figure 5-16B. Sensitivity of relative long-term cost-effectiveness of longer life innovative material to the innovative-traditional price ratio.

Consider a small system of assets located along the same roadway (Table 5-7). If the location costs (i.e., mobilization, traffic control, and user costs) are estimated to be $7,000 per site visit, then what are the optimal replacement times so as to minimize the present value of costs in perpetuity? Assume assets are to be replaced no later than their remaining asset life.

The objective of this problem is to minimize the total lifecycle cost, computed as follows:

$$PV = \sum_{n=1}^{Analysis\ Period} Annual\ Replacement\ Cost * \left(\frac{1}{1+i}\right)^{n}$$

where

$Annual\ Replacement\ Cost = \text{Location Cost} * \sum_{\text{asset}=1}^{3} \text{x}_{\text{asset}}\ \text{Replacement Cost}_{\text{asset}}$;

$x \equiv$ binary decision variable indicating replacement, 1 = replace, 0 = do-nothing;

$n \equiv$ year of potential replacement.

The only constraint is that the remaining asset life must be greater than zero, $RSL \geq 0\ \forall \text{n}$.

Table 5-7. Example data for synchronizing replacement intervals.

Asset	New Construction Asset Life	Remaining Life	Replacement Cost
Pavement Markings	5	3	$200
Traffic Sign	10	4	$300
Traffic Signal	15	5	$500

This optimization problem can be solved using a solver software package, although it is simple enough to solve by inspection, recognizing that

- Ideally an agency would like to coordinate replacements so as to minimize cost.
- The new construction asset life estimates have a common multiple of 5 years.

Therefore, the optimal solution can be seen to be replace

- All assets in year 3.
- Pavement markings every 5 years thereafter (i.e., years 8, 13, 18, 23, 28, 33).
- Traffic signs every 10 years thereafter (i.e., years 13, 23, 33).
- Traffic signals every 15 years thereafter (i.e., years 18, 33).

This produces the same lifecycle profile every 30 years with a present value of $26k.

Alternatively, if an agency did not coordinate replacement schedules and replaced assets at the time each asset's full asset life is reached, the optimal solution can be seen to be replace

- Pavement markings in year 3 and every 5 years thereafter (i.e., years 3, 8, . . . 33).
- Traffic signs in year 4 and every 10 years thereafter (i.e., years 4, 14, 24, 34).
- Traffic signals in year 5 and every 15 years thereafter (i.e., years 5, 20, 35).

Then a common lifecycle profile every 30 years with a present value of $80k is obtained.

This example shows that the strategy of sacrificing 1 year of traffic sign life and 2 years of traffic signal life initially, so as to synchronize replacements, ultimately lowers the present value of costs by $54k ($80k–$26k).

5.3.7 Effect of Funding Constraints

Agencies are constantly faced with the need to do more with less. Decision support tools based on life expectancy and lifecycle cost can help. Following is an example of working around time and budget constraints to maximize the benefit from a limited budget.

Assume an agency has calculated the utility of a set of projects with respect to life expectancy, deterioration, lifecycle cost, and estimated project cost (Table 5-8). Assume a budget of $2.75M.

To select a set of projects, optimization techniques can be applied to the problem:

$$Maximize\ Program\ Utility = \sum_{i}^{m} x_i Utility_i$$

$$Subject\ to\ Program\ Cost \le \sum_{i}^{m} x_i Cost_i$$

where

$x \equiv$ binary decision variable with 1 = program, 0 = do not program;
$m \equiv$ number of potential projects.

This simple example can be readily solved in Microsoft Excel for a small sample size. In this case, the optimal solution would be to replace bridge A, rehabilitate bridge B, replace pipe culvert A, and patch bridge C yielding a total utility of 242 at a cost of $2.675M. The remaining $75k could be carried over to the next planning cycle.

Table 5-8. Example ranked projects with associated utility and cost.

Activity	Utility	Cost
Bridge A replacement	100	$2400k
Bridge B rehabilitation	75	$250k
Box Culvert A replacement	55	$100k
Pipe Culvert A replacement	35	$5k
Bridge C deck patching	32	$20k

5.3.8 Value of Life Expectancy Information

For some of the asset types described in this guide, an agency might not have any data collection processes at all and no way to implement a condition-responsive replacement or life extension program to optimize life expectancy. Usually the cost of data collection is a major barrier to improvement. Here is an example showing the potential cost savings of using life expectancy analysis to design and implement a maintenance program.

5.3.8.1 Value of Quantifying Life Extension

Suppose a life expectancy model predicts a box culvert life of 60 years. If an asset is 45 years old and expert opinion puts the asset life at 50 years, then a replacement project is likely to be programmed within 5 years. However, statistical evidence would suggest this project should not be programmed for another 15 years. The consequences of this can be quantified via lifecycle analysis. Assume the cost of replacement is $100k at a discount rate of 4%.

Remaining EUAC of replacement, as scheduled by expert opinion

$$\$100\text{k} * \frac{0.04}{(1+0.04)^5 - 1} = \$18.46\text{k}$$

Remaining EUAC of replacement, as scheduled by life expectancy modeling

$$\$100\text{k} * \frac{0.04}{(1+0.04)^{15} - 1} = \$4.99\text{k}$$

Based on this analysis, reliance on expert opinion may cost an additional $13.47k over the asset's life depending on the accuracy of the life expectancy model. Thus, reliable life estimates can benefit agencies in setting financial needs and effectively spending taxpayer funds.

5.3.8.2 Value of Additional Explanatory Variables

Life expectancy models can be made more accurate and realistic by the addition of more explanatory variables; but, agencies may be reluctant to add variables because of the implied addition of costs for data collection and/or quality assurance that come with a new data-based application. The following hypothetical example shows how to structure an analysis of the potential benefits of additional data, using a lifecycle cost framework.

In Table 5-9, a number of statistical models were developed to predict the asset life of a highway asset. The series of statistical models employs an increasing number of variables. Each additional variable implies added costs as given in the table. The cost of data collection was then combined with the cost of replacement, which was constant for the particular asset, and the total cost was turned into present worth at perpetuity for the sake of comparison of different models' lifecycle costs.

Table 5-9. Examples of lifecycle cost including data cost.

		No. Of Variables in Model	Asset Life (yr)	Cost for Data	Cost of Replacement	Total Cost	Present Worth at Perpetuity
Increasing number of variables	Practice (rule of thumb)	0	10	0	1000	1000	1590
	Statistical Model 1	1	12	100	1000	1100	1382
	Statistical Model 2	2	13	100	1000	1100	1242
	Statistical Model 3	3	14.5	110	1000	1110	1079
	Statistical Model 4	4	15.5	120	1000	1120	991
	Statistical Model 5	5	17	140	1000	1140	882
	Statistical Model 6	6	18	150	1000	1150	818
	Statistical Model 7	7	18.5	155	1000	1155	788
	Statistical Model 8	8	18.5	160	1000	1160	791
	Statistical Model 9	9	18.5	180	1000	1180	805

Discount rate = 0.05

Once the lifecycle costs of different statistical models, as well as the expert opinion, were converted into present worth at perpetuity, those results were plotted against the number of variables in Figure 5-17. The plot suggests that the total cost declines with an increasing number of variables used in the performance model to predict an asset's life, provided that the added variables enabled an extension of asset life for selected assets as shown in Table 5-9.

Such an analysis could motivate road agencies to collect data and improve the calculation of the life expectancies of highway assets. Some data items, such as the weather data used in some of the example models earlier in this guide, are widely available free of charge. There may be opportunities to spread the cost of certain types of data, such as traffic data, over many asset types. The type of analysis shown in the example can help the agency to optimize its data investment.

5.3.9 Highway Asset Valuation

Reliable estimation of asset life helps improve the accuracy of asset valuation. Most approaches of asset valuation, including the GASB 34 approach, use asset life as a critical variable. The following

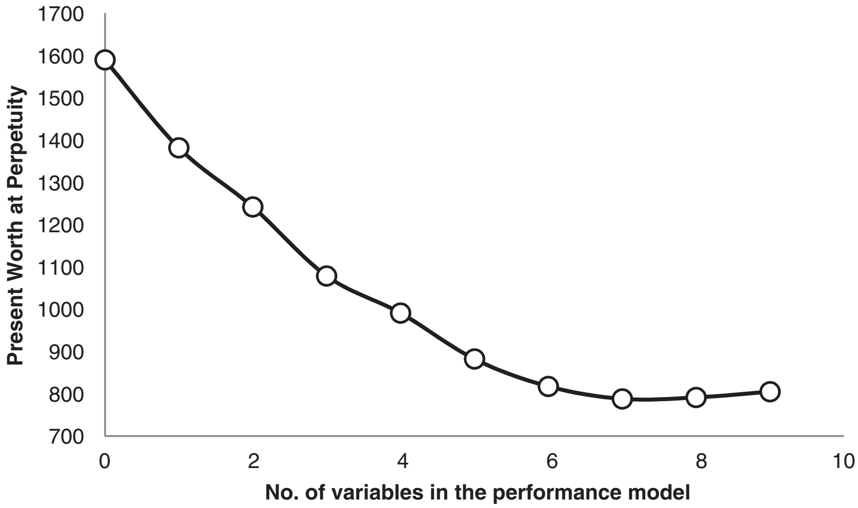


Figure 5-17. Example cost savings due to employing increasingly better performance models.

example involves a box culvert built in 2002 and having a culvert condition rating of 8. The culvert is 8 years of age. Its replacement cost is $123,752 and salvage is assumed to be $0. All costs and values are in 2010 dollars and the analysis year is 2010. The following equations show how asset life is used to find the asset value.

Using the Sum-of-Years Digits (SOYD) functional form for asset depreciation, for example, and assuming a 57-year service life, the asset value at any year can be found.

The depreciation at any year is calculated as:

$$SOYD_t = \frac{N - t + 1}{\left(\frac{N}{2}\right)(N+1)} * (HC - S)$$

Thus, the asset value at any year, V_t, is found as follows

$$V_t = HC - \sum_1^t SOYD_t$$

where $N - t + 1$ is the useful remaining life at beginning of year t; N is the planning period or service life; t is the given year; HC is historical cost adjusted to 2010$ using FHWA Construction Price Index; S is the salvage value.

Thus, the asset value at the 4th year, for example, is found as follows:

$$V_t = \$123{,}752 - \$4{,}562 = \$104{,}923.$$

It can be seen that the asset value, V_t, can be heavily influenced by the service life N.

5.4 Role of a User Group

Earlier chapters showed how to build a constituency for life expectancy analysis that makes it more likely that the necessary data collection and analysis will get done and that the results will be put to work productively. Members of this constituency can do more than make information requests and provide data and resources. If stakeholders are to feel confident that their needs will be met and if the not-invented-here syndrome is to be avoided, stakeholders need to take an active role in application development and subsequent enhancement.

One of the best ways to create involvement and buy-in is to form a user group for the applications to be developed (Figure 5-18). A user group should consist of people who will be hands-on users of the applications, as well as people who may receive and act on the information. Ideally, some of the applications will be of use to the units that collect the necessary data (e.g., workflow management and quality assurance) so representatives of these units can also be user group members.

A user group has the following tasks at different stages of the application lifecycle:

Planning

- Ensure that the user group includes the necessary stakeholders and that all prospective applications are represented.
- Perform or review the asset management self-assessment, specifically concerned with life expectancy analysis and its potential uses (Gordon 2010).
- Review and perform or update, as necessary, the planning steps described in Chapters 1 through 3 of this guide.

- Become familiar with available methods and tools as described in Chapters 4 and 5 of this guide.
- Evaluate possible additional applications and recruit users who may want to see such applications developed. If an application idea has no interested users, this indicates that either the application was not such a good idea after all, the agency already has the tools it needs, the agency is not yet at a maturity level where it can use the application, or some form of organizational change may be necessary first.
- Ensure that senior managers and outside stakeholders are asking questions about how the proposed applications can answer the agency's mission and seeing the possibilities. In other words, make sure there is a demand for the information to be produced.
- Ensure that senior managers and outside stakeholders understand the kinds of information to be provided and the boundaries on coverage, quality, and timeliness that will become possible. In other words, make sure they understand the potential supply of information.
- Review and refine definitions and mockups for compatibility with agency business processes, related information systems, and available data.

Development

- Ensure that in-house and/or consultant labor and resources are made available to develop the applications. Oversee letting and procurement activities as needed. If a consultant is to be hired, members of the user group should select a single author for the Request for Proposals and should review the draft of the document.
- Review the prototypes and documentation developed.
- While prototype development and refinement are underway, resolve issues of terminology, procedures, and data standards. Be prepared to refine and modify these over time, learning from experience with the prototypes. Create and maintain a working document to describe the user group's decisions and recommendations on these matters. Ensure that the developers of the system have input and access to this document and can raise new issues through an organized process.
- Communicate progress to stakeholders, and show results early and often. Convey a constructive and upbeat attitude about the applications.
- Coordinate with committees involved with other aspects of asset management in the agency.
- Assist in maintaining the flow of time and resources necessary to see the application through to completion.

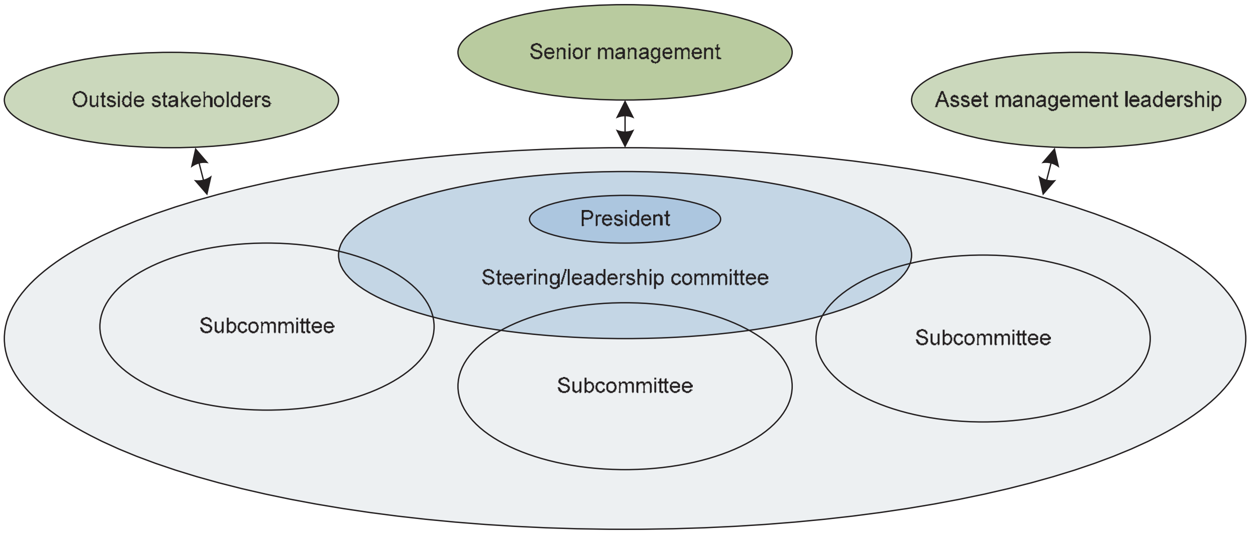


Figure 5-18. Example user group structure.

Production

- Oversee and attend training classes, for new users and applications, and refresher courses for existing users.
- Provide constructive input on new functionality that may be needed.
- Report problems and follow up on solutions.
- Through an organized process, such as voting, advise on priorities for new enhancements.
- Use the products and promote the results to stakeholders.
- Attend conferences and share ideas with other agencies.
- Ensure that the applications contribute to implementation of the Transportation Asset Management Plan (TAMP) (Gordon 2010). Use what is learned from the applications to improve the TAMP and to advance the agency's state of asset management maturity.

Often a user group will be large and may expand over time to include all hands-on users and many indirect users of the applications. Once the group reaches a certain size, it should create sub-groups to whom it delegates many of the tasks above.

5.5 Development of Applications

With so many useful applications, it may be tempting to launch a large system development effort to implement them. Although that has been done, and has often been successful, it is not the only way to proceed.

Another alternative is to select a relatively small subset of applications at first (often just one), and develop a working prototype that addresses the core functions throughout the process—from data collection to analysis to reports. This should be conceived as the smallest possible system that can produce useful outputs and should work from existing data if possible.

Review the prototype first, then gradually expand it to cover more applications and add more features. As part of this review and expansion, identify the data gaps, procedures, and standards that are required in the context of a working application. Having a simple useful program in place works wonders for focusing a development effort, avoiding peripheral features that might or might not eventually be needed, and streamlining the implementation. Priority setting is more natural and harder to avoid if users are ready and eager to put the system to work.

This incremental prototyping style of development is often given the name "agile development" or "extreme programming." Even though it has been styled as a cultural theme for programmers, this type of development is actually driven more by the hands-on users of the systems. It gives users more day-to-day control and involves them more deeply in the creation of the tools they will use. Even if the actual concept, design, and programming are done by an outside consultant, there will not be a "not-invented-here" syndrome if the agency owns the concepts, requirements, and design of their one-of-a-kind product.

CHAPTER 6

Accounting for Uncertainty: How to Improve Life Expectancy Models

Analytical models such as those used for life expectancy analysis can be characterized as “garbage-in/garbage-out,” in that the credibility of the results can be highly dependent on the quality of the inputs. When predicting asset life expectancy, various uncertainties exist (Lin 1995):

- Inherent randomness of structural characteristics (e.g., material properties, section dimensions, loads);
- Inherent randomness of external effects (e.g., environmental conditions, extreme events);
- Maintenance uncertainties (e.g., effectiveness, frequency);
- Statistical uncertainty (e.g., incomplete or errant data from inspections, or errors in estimating parameters of probability models); and
- Model imperfection (e.g., error created through idealized mathematical modeling attempting to describe complex physical phenomena).

Therefore, the prediction of life expectancy is uncertain. The credibility of the results is very important if the investment in the models is to pay off. So it is important to test the models systematically for weaknesses, in a way that sets priorities for improvement. Sensitivity analysis is a good tool to do this.

Through sensitivity analysis, agencies can identify the inputs with the most influence on the life expectancy estimate, quantify the range in potential asset life caused by the uncertain input, and assess the life extension or contraction caused by a unit change in the input. If the effect of an input is considered unreasonable, then the model may require improvements. Alternatively, if the effect of an input is considered reasonable, then data collection efforts may be focused on trying to reduce that uncertainty or contingency funds may be set aside.

Furthermore, this discussion of uncertainty can be taken a step further with the recognition that some planning decisions may be inherently linked to asset life. As a result, there is a risk that less-than-optimal planning decisions may be made as a result of uncertain life expectancy factors and life estimates. Therefore, risk analysis techniques may be appropriate.

Agencies applying risk analysis can make more informed decisions through the probabilistic description of potential asset life and other planning factors such as lifecycle costs and project utility. Unlike sensitivity analysis, risk analysis allows for quantification of the likelihood of various outcomes, upon which agencies can apply risk management techniques to protect against uncertainty.

A further description of sensitivity and risk analysis techniques, as well as examples, is provided in the following sections.

6.1 Sensitivity Analysis of Life Expectancy Models

Sensitivity analysis is a simple method of assessing uncertainty that quantifies how outputs may change when input values are systematically varied on a unit-by-unit basis. In doing so, it is possible to

- Identify the most critical factor driving the output (i.e., the factor that leads to the most widespread range in output values or the largest change in outputs on a unit basis);
- Assess weaknesses in the model (i.e., if the range of outputs produced by a particular input is unreasonable, then the model may require revision);
- Focus data collection (i.e., in order to reduce the uncertainty of an input within control of the agency, additional data collection may be needed);
- Justify contingency plans (i.e., to reduce uncertainty of an input outside the control of the agency (e.g., climate conditions), contingency plans to deal with potential outputs may be needed); and
- Set priorities for improvements (i.e., if an input produces more (or less) favorable outputs, then attempts can be made to maximize (or minimize) the input in future cases).

The most common presentations of sensitivity analysis results are through the use of tornado (Figure 6-1), spider (Figure 6-2), and elasticity diagrams which describe how the output changes when each input is varied from its minimum to maximum values while holding all others at their average values. A tornado diagram presents the range of outputs produced by each input in a descending order of influence. A spider diagram graphically portrays the influence of each input, where the largest magnitude slope is the most influential and the sign of the slope indicates a positive or negative effect on the output. An elasticity diagram is similar to a spider diagram, except that the percent change in output is assessed against a percent change in input for different points in time.

Additionally, the influence of a unit change from the current input value is often assessed as a function of the parameter estimate or coefficient.

Linear regression models have the simplest sensitivity interpretation. In these models, the coefficient directly indicates how much the output changes for every unit change in an input. For example, in the following life expectancy model, an asset life extension of 2 years is predicted for every unit change in y.

$$\text{Asset life} = 35 - 3x + 2y$$

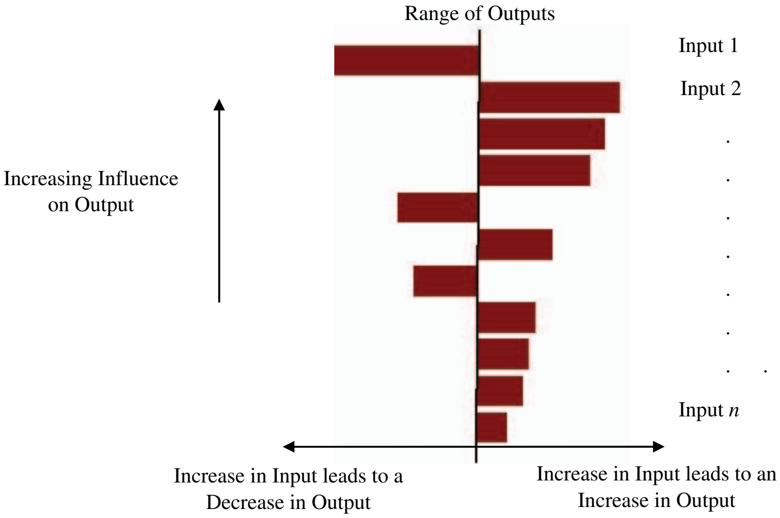


Figure 6-1. Example of a tornado diagram *(FHWA 2006).*

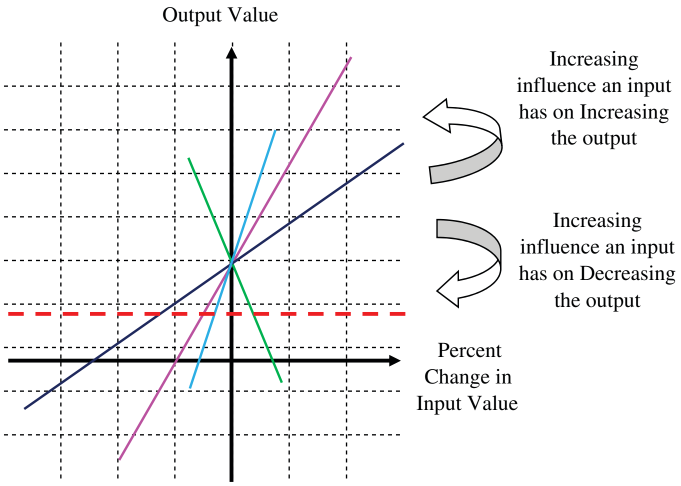


Figure 6-2. ***Example of a spider diagram*** *(van Dorp 2009).*

When dealing with transformed variables, the coefficient will have to be transformed back. For instance, in the following model, an asset life extension of just over 7 years (=exp(2)) is obtained for every unit change in y.

$$\text{Natural Log of Asset life} = 35 - 3x + 2y$$

For non-parametric models, sensitivity analysis can still be performed by comparing different groupings of data. For instance, if Markov chains are used to analyze bridge life, the life estimate of bridges with one level of maintenance can be compared against the life estimate with a higher level of maintenance.

Although conceptually the same, various terms are applied to the description of a factor's sensitivity. For instance, in survival models, this unit change is often termed an acceleration parameter. These parameters represent the stretching or contracting of the survival curve for every unit change in one of the inputs. In ordered probit models, unit changes are often termed marginal effects. These effects refer to the change in probability of being in one state given a unit change in an input.

A direct comparison of coefficients does not always indicate which input has the greatest influence on the output. For a fair comparison of the influence of each input, the relative parameter strength can be used. The coefficients can be normalized by dividing each input by its average unit value, which results in a unitless comparison of the influence of each factor.

To demonstrate how to interpret the results, the researchers conducted a sensitivity analysis of the pipe culvert life expectancy model in Section 4.1.1.5. If one input at a time is varied from its minimum to maximum values (Table 6-1) while holding all others at their average values, the asset predictions in Table 6-2 are obtained. The resulting tornado diagram visualizing the ranges in estimates in Figure 6-3 is then produced.

As is apparent in the tornado diagram and in tabular form, the most influential factors for this life expectancy model are the climate conditions. For this analysis, the range of factors was set based on the minimum, average, and maximum values for the entire collected pipe culvert database. However, when assessing the sensitivity of life at a single location, far more certainty may be incorporated into the assessment.

Table 6-1. Range of values for example sensitivity analysis.

Life expectancy factor	Minimum value	Average value	Maximum value
Metal material type indicator (1 if metal, 0 otherwise)	0	1	1
Average annual freeze/thaw cycles	95	130	150
Soil corrosiveness potential (1 if high, 0 otherwise)	0	0	1
Ditch inlet/outlet indicator (1 if ditch inlet/outlet, 0 otherwise)	0	1	1
Coating application indicator (1 if coated, 0 otherwise)	0	1	1
Average annual temperature in °F	45	49	53
Average annual precipitation in inches	38	43	47

Table 6-2. Range of asset life estimates for example sensitivity analysis.

Life expectancy factor	Asset life at minimum values	Asset life at maximum value	Range
Metal material type indicator (1 if metal, 0 otherwise)	54	67	+13
Average annual freeze/thaw cycles	93	56	-37
Soil corrosiveness potential (1 if high, 0 otherwise)	67	58	-9
Ditch inlet/outlet indicator (1 if ditch inlet/outlet, 0 otherwise)	63	67	+4
Coating application indicator (1 if coated, 0 otherwise)	61	67	+6
Average annual temperature in °F	46	99	+53
Average annual precipitation in inches	109	46	-63
Asset life at Average Values		67	

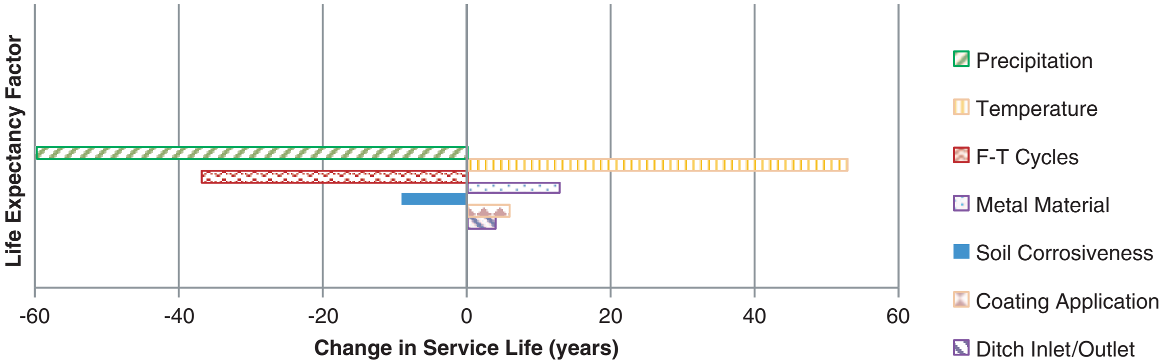


Figure 6-3. Tornado diagram of example sensitivity analysis.

Additionally, for factors within the asset manager's control, this particular model suggests that using metal culverts can add 13 years to the asset's life, replacing corrosive soils may extend its life 9 years, coating an asset may extend its life 6 years, and using ditch inlets/outlets to filter contaminants may extend its life 4 years. For every additional unit of precipitation from the average, asset life is predicted to decline by 6.2 years {67 * [exp(−.097)−1]}. Similarly, asset life is predicted to increase by 6.8 years for every unit change in temperature from the average and decrease by −0.6 years for every change in freeze/thaw cycles from the average.

6.2 Risk Analysis of Life Expectancy Models

A more in-depth assessment of uncertainty in life expectancy estimates can be done by way of risk analysis. Risk is defined as an uncertain outcome with an inherent likelihood and consequence (typically, an undesirable consequence). Due to the uncertainties associated with asset life expectancy and life expectancy factors, agencies stand at a risk of making less-than-optimal planning decisions. Examples, provided in this guidebook and the accompanying report, include an assessment of the uncertainty of future asset life due to uncertain climate and the uncertainty of over/underestimating of long-term planning needs due to uncertain asset life.

Risk analysis can be incorporated into asset management through four steps (Ford 2009):

- Risk Identification—describe the consequences and the conditions that may influence the likelihood of the risk (e.g., risk of scheduling asset replacement project before the full asset life is reached, leading to increased lifecycle costs caused by uncertain life expectancy estimates or factors);
- Risk Assessment—quantify the consequences and likelihood of the risk (e.g., consequence = increase in lifecycle cost; and likelihood = probability of lifecycle cost increase given the survival probabilities of the asset);
- Risk Management—decide on a mitigation strategy based on the consequences and likelihood of the risk (e.g., conduct additional asset inspections/mechanistic testing); and
- Risk Monitoring—measure the effectiveness of the mitigation strategy (e.g., were lifecycle costs reduced by applying the management strategy?).

Of these steps, the most relevant to the asset manager's task of life expectancy determination is the risk assessment step. This assessment differs from sensitivity analysis in that the **likelihood** of a range of outputs can be quantified.

A typical risk assessment involves two statistical techniques: distribution fitting and Monte Carlo Simulation (Ashley et al. 2006). Distributions can be fit using software or by conducting various goodness-of-fit tests (e.g., Kolmogorov-Smirnov, Anderson Darling, Chi-squared). Life expectancy factors such as climate variables have relatively well-known distributions. For instance, long-term NOAA data are generally assumed to be normally distributed (Whitehurst 2008). To assess the likelihood of outputs, it is then a matter of conducting a Monte Carlo Simulation.

Monte Carlo Simulation is the process of randomly sampling values from each input distribution, inputting these values into the model, and finally assessing the likelihood of the outputs (Figure 6-4).

In the context of life expectancy, risk analysis can be conducted in two stages:

1. Assess the likelihood of asset life estimates due to uncertain life expectancy factors; and
2. Assess the likelihood of lifecycle costs and other planning factors due to uncertain asset life estimates.

Vulnerability relates to hazardous or threatening events and vulnerability analysis often simulates attacks on a system and evaluates the system responses. Significant amounts of literature exist on the vulnerability of major assets (e.g., pavements and bridges) to hazardous events (e.g., earthquake, flood, landslide, and fire). Approaches discussed in the literature could also be used to analyze vulnerability of less-studied assets such as pavement marking, traffic signs, and signal and lighting structures. Historical data on flooding, landslides, fire, and earthquakes are typically available in the public domain; thus, assessing the vulnerability of less-studied assets to these events can be analyzed using the data available. However, data on other events, such as collisions between boats and bridge piers, or between vehicles and guardrails or with other road appurtenances, hazmat spills, and terror events are quite rare. As such, any analysis of vulnerability to such events will be expected to rely heavily on expert opinion.

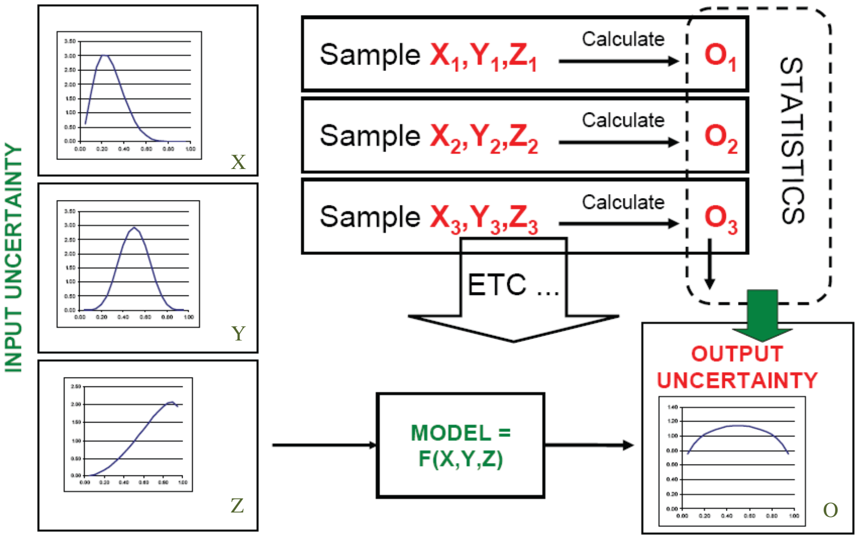


***Figure 6-4. Monte Carlo simulation process** (van Dorp 2009).*

6.2.1 Example Risk Assessment of Uncertain Life Expectancy Factors

Continuing with the sensitivity analysis example in Section 6.1, let us suppose an agency now wishes to know the likelihood of asset life at one location with uncertain temperature and precipitation values. Via risk analysis, this can be done by fitting distributions and applying Monte Carlo Simulation techniques.

For this example, let us assume the distributions in Table 6-3. By randomly sampling these distributions, a planner recognizes that expected climate conditions over the life of an asset are not certain, and the life expectancy predicted therefore is not certain. By randomly sampling these distributions, a range of survival curves is obtained (Figure 6-5).

Wider confidence intervals represent more uncertainty in the estimate. For instance, from Figure 6-6, it can be seen that the uncertainty surrounding asset survival probability is relatively low within the first 20 years but then increases until around year 80 before decreasing again.

The uncertainty surrounding the asset life prediction can be assessed by analyzing how the 50th percentile asset life changes for each random sample of the inputs. As a result of this analysis, the distribution (Figure 6-7) representing how the average life changes, given random temperature and precipitation values, is obtained. Although the median life of the distribution remains at 67 years (see Section 6.1), the most likely life estimate now is actually calculated to be 48 years.

Given the uncertainty in temperature and Precipitation values, this analysis suggests a 90% confidence interval of [26 years, 173 years] and a 68% confidence interval of [38 years, 119 years].

Table 6-3. Distributions for example risk analysis.

Life Expectancy Factor	Mean	Standard Deviation
Normal annual temperature in °F	49	1
Normal annual precipitation in inches	43	6

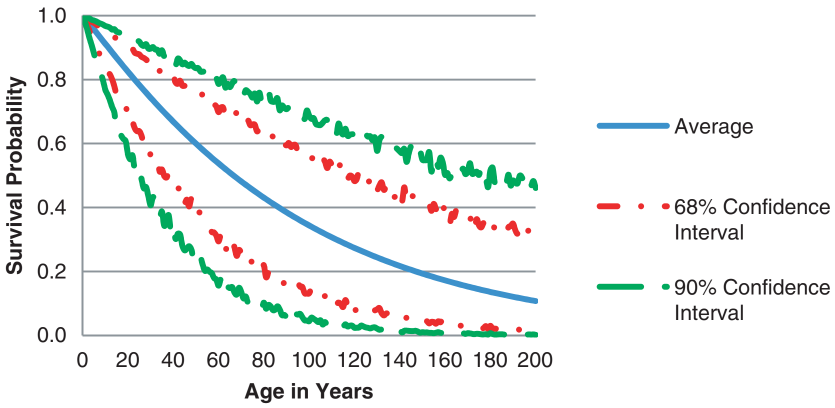


Figure 6-5. Example uncertainty surrounding asset survival curve.

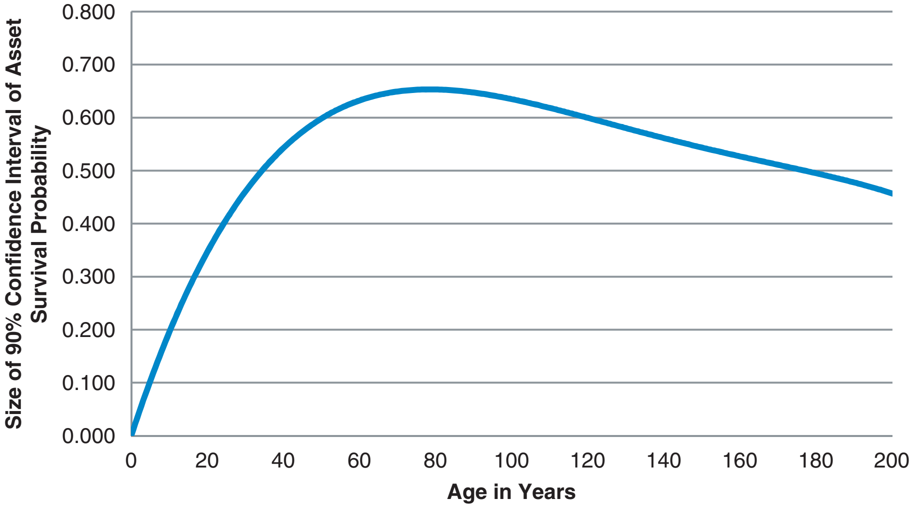


Figure 6-6. Example uncertainty by assessment of confidence interval size.

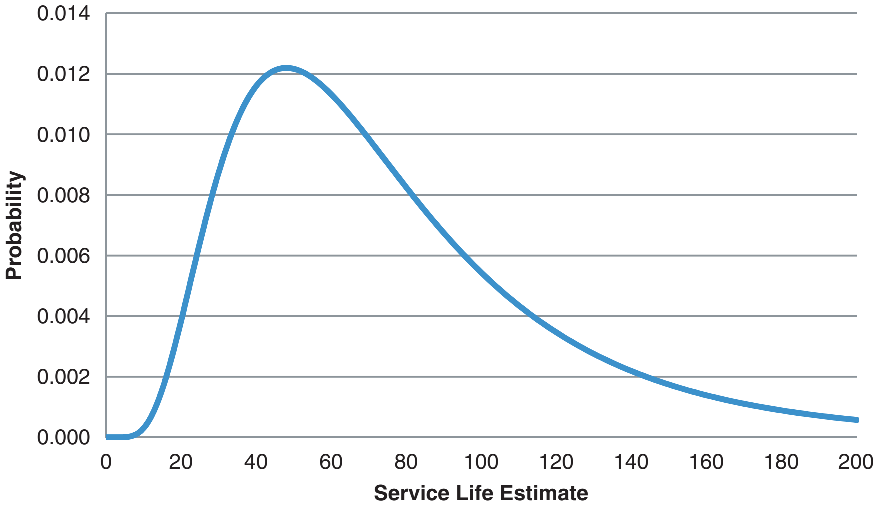


Figure 6-7. Example uncertainty surrounding life expectancy estimate.

The wide variation in asset life estimates demonstrates that care must be taken when basing planning decisions on remaining life. Actual climate conditions are likely to be more certain, resulting in a narrower range of predictions. To further illustrate the risk associated with uncertain asset life, the following section demonstrates how a risk analysis can be repeated with asset life as the uncertain input and various planning decisions as the outputs.

6.2.2 Example Risk Assessment of Uncertain Estimates of Asset Life

Asset life estimates can be incorporated into various business processes such as assessing budget needs, calculating lifecycle costs, and ranking projects.

If setting budget needs, the expected amount of money that should be set aside for replacement can be taken as the product of the probability of needing to replace an asset within a certain planning horizon and the cost of replacement for that asset. The expected network needs are then the total for all assets. If the time of replacement is considered the same as the predicted asset life, then the expected budget needs can be readily calculated. For example, consider a pipe culvert that is estimated to cost $1,000 to replace and the planned time for replacement taken as the distribution in Figure 6-7. The expected needs for this one asset in a 25-year planning horizon are then

$$\mathrm{E}[\$] = \text{Replacement Cost} * \mathrm{P}(\mathrm{SL} \le 25 \text{ years})$$

The probability of an asset life estimate being less than 25 years is equivalent to the area under the curve shown in Figure 6-8, assuming new construction. In this case, there is only a 4% chance of a planner predicting the asset to need replacement within the planning horizon. Therefore, only $44 ($1,000 * 0.044) may need to be added to the total budget on account of this asset.

Similarly, the risk of planning for inaccurate lifecycle costs can be calculated. For example, if a manager is interested in an asset's present value, assuming no maintenance or rehabilitation, and the time of replacement is considered to be the estimated asset life, then

$$E[PV] = \sum\left[\left(\frac{1}{1+i}\right)^{SL} \times FV\right] \times P(SL)$$

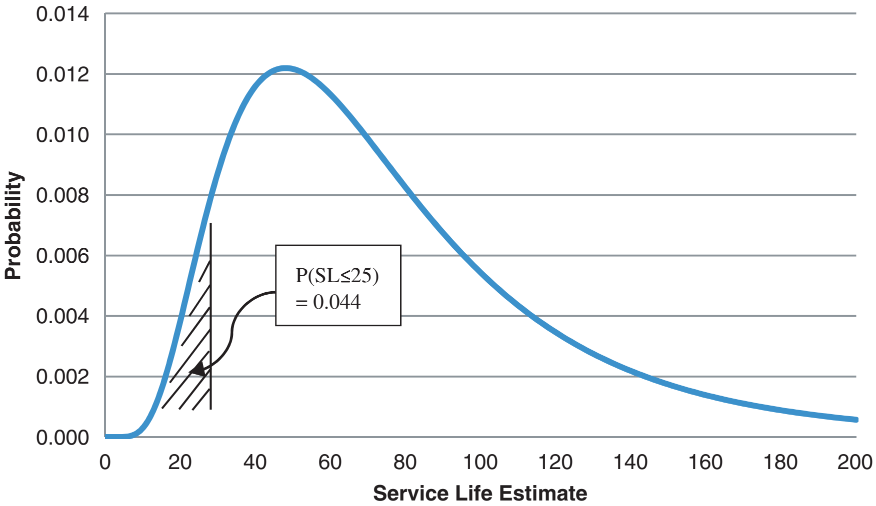


Figure 6-8. Example probability of replacement in 25-year planning horizon.

If a discount rate of 4% is assumed, with the same replacement cost and asset life distribution, then the distribution of present value in Figure 6-9 is obtained, with an expected present value of $113.

Additionally, for agencies that use remaining asset life as a factor in ranking projects, the utility associated with a project may be considered uncertain due to the risk of inaccurate life estimates. For example, let us consider a utility curve developed through surveying INDOT officials (Figure 6-10).

Assume now that a culvert with the estimated life distribution in Figure 6-7 is 45 years old and we would like to predict the change in utility associated with a replacement project in 5 years. If we assume a life of 67 years (the median life predicted for this example—calculated in Section 6.1), then the remaining asset life at the time of potential replacement for this asset is 17 years. From our utility curve, we could then conclude that planning for replacement at this time would not improve our utility.

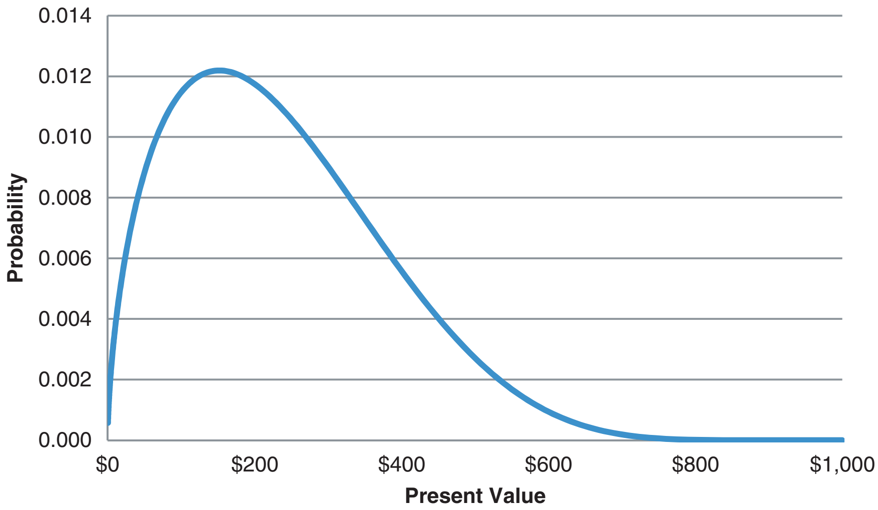


Figure 6-9. Example probability of estimated present value.

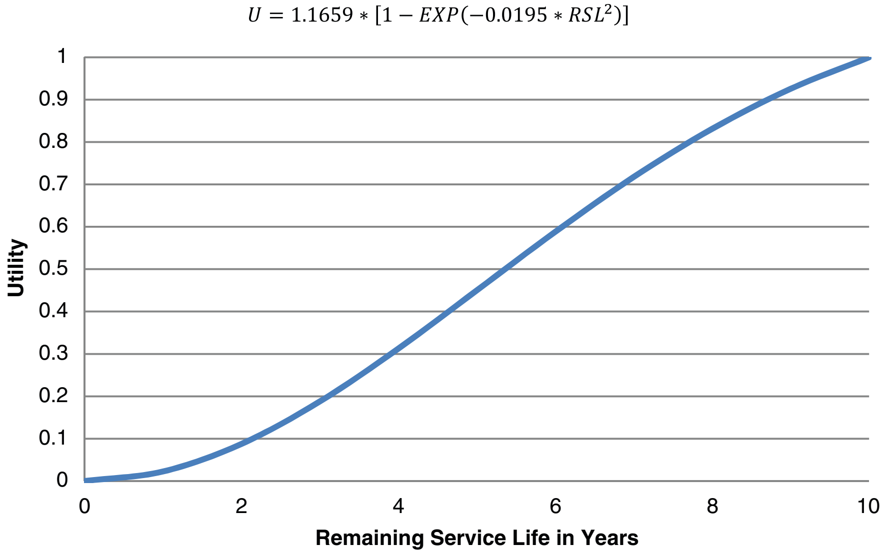


***Figure 6-10. Example remaining life utility curve** (Li and Sinha, 2004).*

However, given that asset life is uncertain, there is some probability associated with this project being worthwhile. For instance, the probability of this project actually having the highest possible change in utility is

$$P(\Delta U = 1) = P(RSL \leq 0) \text{ and } P(SL \geq 10)$$

For the distribution in this example, this probability turns out to be 30.6%. Similarly, the probability of the asset having no change in utility is 58.7% and the expected utility for this potential project is 36. This finding shows that the confidence that this project will have the predicted utility is lower than some planners may assume, showing the risk of planning and potentially programming less-than-optimal projects.

Uncertainty surrounding life expectancy factors and estimates can highlight deficiencies in the model, identify the most influential factors, and quantify the effect on basic planning decisions. Therefore, it is up to the agency to sift through the quality of its life estimates and to manage any potential risk in planning for an errant forecast.

CHAPTER 7

Ensure Implementation: How to Improve Life Expectancy Models

Improvements in life expectancy analysis, by implementing the techniques in this guide, undoubtedly will involve some extra investment in data collection, training, staff time, and management attention. Stakeholders making this investment will want to ensure that the investment pays off. Staff members who work to improve their professional capabilities will want to know that this improvement enhances their professional advancement and the quality of service they provide to the public. As a whole, the agency will be successful in extending its implementation of these methods as long as the stakeholders, internal and external, continue to find the effort worthwhile.

7.1 Measuring and Promoting Success

Like any new asset management technique, the success of life expectancy analysis will be judged by whether stakeholders think their objectives are being served. There are both quantitative and qualitative ways of assessing this, all stemming from the agency's original goals and objectives for starting the process.

One way of approaching this is to ask a series of questions.

Long-term view

- Is the agency now confident in publishing life expectancy estimates and using them to evaluate and anchor budgetary requests?
- Do senior managers have confidence that they know how much it will cost in the long term to sustain the desired level of service?
- Do outside stakeholders agree with management estimates of the long-term cost of sustaining the desired level of service?
- Do senior managers and stakeholders know what level of service can be sustained under current or proposed future funding levels?

Transparency

- Is there a public comparison of forecasted versus actual life expectancies?
- Are actions taken in response to life expectancy estimates and findings and do stakeholders know what these actions are?
- Are comparisons routinely and publicly made of the agency's performance against peer agencies and against itself over time?

Levels of service

- Can the agency accurately measure, track, and publish the level of service it is currently providing?

- Are life extension and replacement decisions accurately timed to avoid interruptions in service while minimizing costs?
- Is the agency reducing the annual number of traffic disruptions resulting from planned and unplanned maintenance, repair, and replacement activity?

Efficiency

- Is the agency improving in its quantitative performance in relation to the cost of providing the desired levels of service?
- Can the agency show, from its actual data, that its more refined timing of life extension and replacement actions is saving money, relative to earlier practice?
- Does the agency routinely compute, and effectively communicate, the lifecycle costs of its services? Are these costs showing a clear trend of improvement?

Agency competitiveness

- Is the agency using its asset management information to secure adequate funding?
- Are legislators confident that the agency is doing everything it can to control costs?
- Is the agency able to maintain adequate funding levels over time in the face of competing uses of the money?

Constructive relationships

- Is the agency working actively with outside stakeholders on strategies to maintain and enhance the level of service provided to the public?
- Do outside stakeholders understand how their own interests are served by maintaining the agency's level-of-service objectives?
- Do legislators and funding bodies rely on the agency's models of the relationship between level of service and funding?

Although these questions may seem vague, agencies have developed very specific tools and methods to conduct these measurements in the context of advancing their asset management maturity level. Gordon (2010) contains a wealth of case studies on these efforts. It is especially important to use asset management tools, such as life expectancy analysis, to build credibility by communicating the agency's successes in satisfying published goals.

7.2 Incorporation into Management Systems

The kind of proactive decision-making needed of agencies in the more mature stages of asset management requires adoption and consistent use of analysis tools, especially deterioration and lifecycle cost models. Many agencies have responded to this need by adopting pavement and bridge management systems. Many of the techniques described in this guide can be found in those systems.

An advantage of using the management system approach is that the tools for data collection, quality assurance, analysis, and reporting are all integrated under one system architecture, helping to ensure their consistency. Agencies not only invest in the creation of these systems, but in the procedures surrounding them, including manuals and training that reinforce the correct use of the systems.

Similarly, implementation of these techniques on assets other than pavements and bridges can be solidified by incorporating them in maintenance planning systems or asset management systems. Potential models for this type of system have been documented in several recent reports (Harrison et al. 2004, Cambridge et al. 2005, and Patidar et al. 2007).

One criticism of this approach is that it is often difficult to develop the data collection and data management tools while developing the analysis methods and management reports. Agencies often prefer to take it a step at a time, first fully implementing inspection and quality assurance, with very simple management reports, before developing analysis tools such as lifecycle cost models.

This is partly why many more agencies have implemented the data collection parts of their pavement and bridge management systems than have implemented the management decision support parts (Thompson 2006). Other reasons include

- Data collection and management systems are more easily standardized into off-the-shelf software systems. Decision support systems are more often tailored to the needs of specific agencies and are harder to standardize.
- The kinds of expertise necessary to develop decision support analysis tools differ from the expertise necessary to develop data capture and database management tools.
- Management requirements for analytical reports change relatively frequently. Management turnover, changes in stakeholders, political trends, and continuous learning all cause changes in perspectives and requirements.
- Developing management tools that fit evolving agency requirements is more incremental, involving smaller and more frequent updates, than the traditional software development cycle used on the large systems that transportation agencies traditionally procure. Management tools have had an uncomfortable fit with the traditional information technology business model.

Because of all these factors, the de facto business model for development and enhancement of analysis tools in asset management has been more like the evolving model of Software as a Service (SaaS). In this model, software systems are kept very modular, each module being small and updated frequently. These systems are loosely joined by standardized interfaces, agency procedural manuals, and database schemas.

The most successful SaaS systems have many software authors, each with very specialized capabilities, from within the agency and from various private-sector organizations. There is a high level of interaction between the end-users and the software authors. The development tools are often off-the-shelf end-user tools such as Microsoft Office (Word, Excel, and Access), ArcGIS, and Crystal Reports. Very often some of the agency's end-users develop technical knowledge of the development tools and want to take an active role in system development if they are to be willing to accept the final product.

It is likely that most of the decision support models developed as a result of this guide will end up being suites of Microsoft Excel spreadsheet models and reports that are added onto existing agency databases and maintenance management systems. For many agencies, this path has proven to be the quickest way to get the tools into management hands and put them to work. It is also the path of least resistance to ensure that the tools are continuously improved.

CHAPTER 8

Conclusions

Life expectancy on the surface appears to be a simple, common-sense concept. However, this guide has shown that the concept has many different applications, touching various business processes in a transportation agency, requiring careful attention to consistent methods and definitions. Like any analysis tool, life expectancy is very sensitive to the quality of the data available and is often sensitive to agency policy and programming decisions. The chapters of this guide were structured to ensure that the agency chooses the appropriate tools for the job and develops them in the most cost-effective way possible. The main themes are

1. Defining the scope of the analysis, including identification of the people who will use the information, how they will use it, and the types of assets for which it will be used. All users need to have a consistent understanding of the results and be in a position to put the new information to work.
2. Planning for implementation, which includes the development of a detailed plan for the processes and applications that will use the information. Because "information is power," the introduction of new information in an agency can affect responsibilities and accountabilities, which are often sensitive subjects. It is important to recognize and plan for the organizational changes that can occur.
3. Establishing the framework, which includes having a clear definition of "end-of-life" as it relates to the decisions that the agency makes on a routine basis. Having clear definitions will ensure that everyone who uses the new analysis will understand what it means and how to use it correctly. It is important at this stage to ensure that the necessary input data are available and that it is clear how the information will be delivered to users in the form of applications and reports. It is important to gain buy-in from all the people who can affect successful implementation.
4. Development of foundation tools, which are the methods for computing life expectancy. This includes the development of statistical models from historical data and the use of these models with new data in order to make future predictions of end-of-life.
5. Development of applications, where the foundation tools are put to work on routine agency processes, such as analysis of alternatives, lifecycle cost analysis, treatment selection, treatment timing, priority setting, performance target-setting, budgeting, and policy-making.
6. Continuous improvement, where the agency monitors the accuracy and sensitivity of the analysis tools and works to improve them over time.
7. Prolonging of implementation, which involves building the life expectancy analysis into information systems and the culture so the results of implementation remain relevant and useful over the long term.

The completion of this logical sequence of activities will help the agency make more objective, quantitative decisions; enhance agency credibility with and accountability to stakeholders; and improve the agency's ability to serve the public interest with asset management.

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Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation