Chapter 4
Asset Performance

Section 4.1

Introduction to Life Cycle Management introduces life cycle management and describes its importance to TAM, through examples of agency practice and how-to guides. It also stresses the importance of using performance objectives to drive life cycle decisions.

Section 4.2

Common Approaches to Managing Transportation Assets describes how the reliability-centered maintenance (RCM) process is applied to transportation infrastructure assets in order to select an effective life cycle management approach for any class of assets.

Section 4.3

Managing Assets Over Their Life Cycles describes how different life cycle approaches can be applied to managing assets. Guidance is provided for applying the common approaches described in section 4.2. the section provides information on the various technical aspects of each approach, and how life cycle management approaches can be implemented within agency organizations and business practices.

Chapter 4

Maximizing the Performance of Transportation Assets

Highway infrastructure represents a significant investment of public funds. With that investment comes the expectation that infrastructure assets will provide a safe and efficient means of travel to the public and the investment in these assets will be preserved. This chapter covers the strategies and techniques transportation agencies can employ to maximize the service life and performance of transportation assets and thus the service those assets provide to the traveling public. A focus is placed on life cycle planning which seeks to develop a structured approach to maximizing asset service life at the lowest practicable cost.

Key Terms

Asset Life Cycle.
The management stages of an asset including planning, construction, maintenance, rehabilitation, and reconstruction or replacement.

Asset Performance.
The ability of the asset to fulfill its intended function. While condition is sometimes used as a proxy for performance (e.g. pavements), for other roadway assets such as lighting, safety equipment and bridges, performance may not be adequately evaluated using condition alone. An asset's service requirement often helps select performance criteria for performance management, forecasting and measurement.

Capital work / investments.
Activities that create, expand, improve, renew, or extend the service life of transportation infrastructure. Common types capital investments include acquisition, new construction, enhancement, expansion, modernization, rehabilitation, and reconstruction.

Condition-Based Maintenance Management.
A maintenance approach in which maintenance activities are scheduled based on regularly-monitored performance. Typically, used on assets with long asset life cycles, and can sometimes lead to "asset preservation" interventions.

Interval-Based Maintenance Management.
A maintenance approach in which maintenance activities are scheduled at specific time intervals based on an analysis of asset performance. Used on assets with short or long life cycles and can sometimes lead to "asset preservation" interventions.

Life Cycle Planning (LCP).
A process to estimate the cost of managing an asset class, or asset sub-group over its life with consideration for minimizing cost, while preserving or improving the condition (23 CFR 515.5).

Life Cycle Strategy.
A standard, documented approach, resulting from LCP, that applies maintenance, preservation, and capital investment actions at each appropriate stage of the asset life cycle to maximize asset performance with available funding.

Maintenance.
Activities that are undertaken to prevent or address defects or usage effects that, if carried out, help ensure the asset achieves its expected service life. Examples of maintenance activities include, but are not limited to, pothole repair, crack sealing, painting, debris clearing, vegetation control, graffiti removal, and snow and ice control. For large complex assets, such as bridges or traffic signal installations, maintenance may include replacement of individual components. For small inexpensive assets, such as ground-mounted signs, pavement markings, all activities performed on an existing asset, including replacement, may be considered maintenance.

Maintenance Level of Service.
The desired performance established for an asset in terms of a measure that can be used to track the effectiveness of maintenance activities. Maintenance level of service is commonly established based on measurable conditions, or customer ratings where different measured attributes for different assets are related to a single scale. The common scale is typically A through E, or 1 to 5, but can be any consistent scale. Maintenance level of service can be used in planning and evaluating the appropriate level for various maintenance activities with available funds.

Operations.
Activities that allow service to be provided by the asset, however are not actions focused on the asset specifically. Snow plowing, sweeping, bridge operations, ITS communications, signal coordination, lane reversals and other activities that allow that asset to delivery mobility for users are examples.

Preservation.
Activities performed to achieve or extend the service lives of existing infrastructure assets, without changing the operational nature of the asset. Preservation may include both maintenance and capital investment activities.

Reactive Maintenance Management.
An approach in which maintenance activities are performed in response to reported asset failures or events, such as a vehicle collision or storm damage.

Reliability Centered Maintenance.
An approach for determining the maintenance requirement for any physical asset, based on its operating context within the agency. Typically, used on assets with shorter asset life cycles.

A Note on Terminology.
Maintenance, as defined at the start of this chapter, refers predominantly to Routine Maintenance, is not normally a capital investment, and does not increase expected asset service life. It is an intervention that may improve condition (e.g. filing a pothole) and ensures service life is realized.This definition is not universal, particularly given FHWA funding eligibility definitions. Maintenance in some jurisdictions sometimes refers to capital betterments, or service life altering interventions. Effort has been made to achieve consistency in the use of this terminology in this chapter. Instances where the term maintenance has a broader meaning are specifically indicated in the text.

Section 4.1

Introduction to Life Cycle Management

This section introduces life cycle planning and describes its importance for TAM through examples of agency practice and a how-to guide.

This section has three parts:

1. **Defining Life Cycle Management.** All transportation infrastructure assets have a life cycle, the stages asset travel from conception to removal or replacement. Life cycle management is the practice of considering the needs of infrastructure assets throughout their service lives, along with the cost and benefits of preventive and corrective actions that can be taken to optimize service life and to reduce the long-term cost of preserving asset condition.
2. **Establishing Asset Service and Performance Levels.** This section introduces the importance of establishing desired performance levels to drive the selection of the most appropriate life cycle scenario.
3. **Developing Life Cycle Strategies.** By establishing sound long-term strategies, agencies can extract the most value to the extent practicable with available revenue while minimizing future costs.

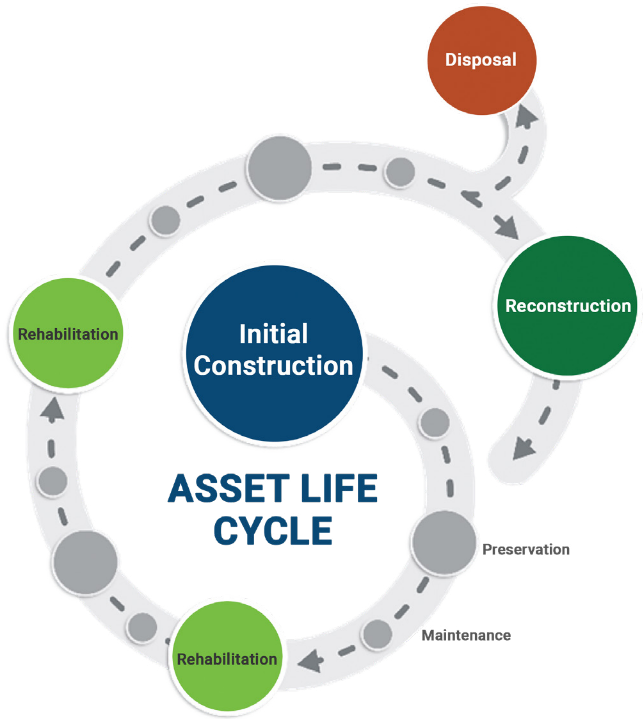
Defining Life Cycle Management

Through life cycle management, agencies employ data on asset condition, treatment options, costs, deterioration rates, replacement cycles, and other factors to determine the most cost-effective, long-term strategies for managing assets throughout their lives.

All transportation infrastructure assets have a life cycle, which includes several stages from initial construction to removal or replacement (see figure 4.1). Life cycle management is an investment approach that considers maintenance, renewal, replacement, or repair options through an asset's service life with the intent to maximize the benefit provided by the asset at the minimum practicable cost. It employs data on asset condition, treatment options, costs, deterioration rates, replacement cycles, and other factors to evaluate trade-offs between possible investment strategies and treatment timings. Effective life cycle management requires knowledge of the agency's strategic priorities and an understanding of the performance criteria driving investment decisions, so the right management strategy can be identified and implemented for each asset class. Aligning asset management measures with agency priorities ensures the investments made to extend asset service life provide the maximum impact to the agency's long-term goals.

Figure 4.1 illustrates a variety of interventions that occur over an asset life cycle. The larger circles represented in the figure are service life altering, and represent a capital investment in infrastructure. Capital investments provide significant life extension, and may alter or enhance the operational nature of the asset, e.g. expand capacity, without fully replacing the asset. Maintenance (reactive, interval based and routine) activities are required throughout the life cycle to ensure the asset achieves its service life. Preservation treatments restore condition or performance to achieve service life, and may extend service life as well, but do not significantly alter the operational nature of the asset. Some agencies may capitalize investment in these preservation activities; however, regardless of the timing and character of the selected interventions, all of them are part of the life cycle management process. More (lower cost) maintenance in-

Figure 4.1 Stages of an asset life cycle

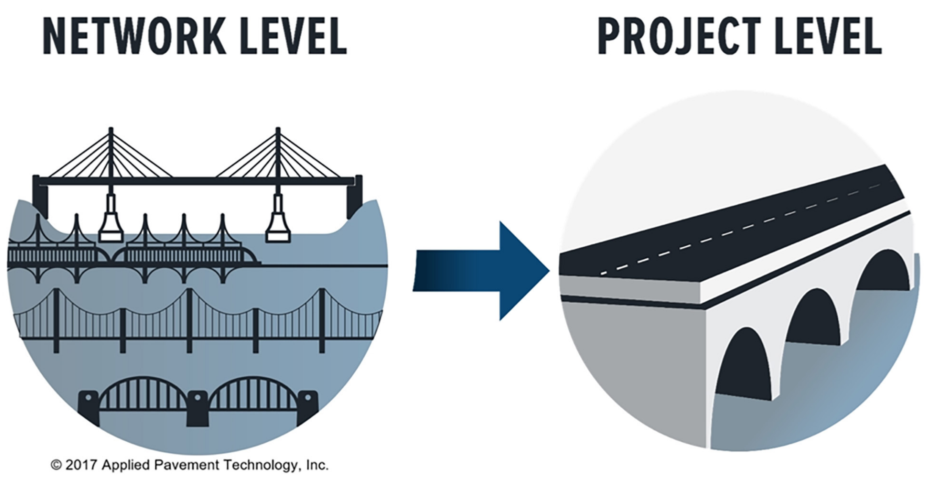


terventions can offset the number and cost of the larger (and more costly) interventions. Balancing the right intervention, at the right time, can greatly reduce the overall investment needed for infrastructure to be reliably available for providing service.

Life cycle management can be used at both network level and at project level. At network-level, life cycle management considers the needs of an entire asset class, as well as the available funding, to determine the most appropriate life-cycle strategies. For example, analysis can establish the optimal proportions of overall investment that should be allocated to different types of interventions over the network, to minimize investment to achieve performance targets or an average condition level. At a project level, life cycle management is commonly used to develop asset-specific strategies. Project level life cycle plans provide input into the network level life cycle plans. Large bridges or other distinct network components are often planned and managed in this manner.

Life Cycle Cost Analysis (LCCA) is an engineering-economics approach that can be used to quantify the differential costs of alternative design approaches. Network level life cycle management, while a more wholistic process that manages every stage of an asset's life, may employ LCCA or other forms of analysis to inform management decision-making. Figure 4.2 highlights some of the major differences between life cycle management and life cycle cost analysis. At the network level, LCCA can be used to understand how to best manage the network as it ages. At a project level, it is used to understand what are the most effective actions to be taken on the assets within the project scope at the time of project delivery. Both network level and project level analyses contain many aspects of engineering economic analysis, such as consideration of user benefits, user costs, and the time-value of money to identify alternatives that represent the lowest practicable life cycle cost over the analysis period to achieve the desired objectives.

Figure 4.2 Attributes of network level life cycle management and project level life cycle cost analysis



- High level.
- One asset class or subclass.
- Multiple locations.
- Looks at impacts of varied treatment timing.
- Considers future cost changes.

- Detailed.
- Multiple asset classes.
- Single location.
- Treatment timing fixed for all options.
- Uses discount rate.

Decision Making Context

Life cycle management is driven by the need for owners to provide consistent service to those that use the transportation system with the resources available. Infrastructure decision making can take place at several levels within an organization, and in each case, considers different but often interrelated factors. These are illustrated in table 4.1.

Figure 4.3 Analysis of KYTC Future Costs Under Two Strategies.

Source: Kentucky Transportation Cabinet Transportation Asset Management Plan. 2018.

Practice Examples
Pavement Life Cycle Management

Kentucky Transportation Cabinet (KYTC)

In the early 2000s, KYTC found that the cost of hot-mix asphalt (HMA) was increasing faster than its budget to maintain pavement conditions. In response, KYTC evaluated the feasibility of strategies that relied heavily on preventive maintenance overlays such as thin HMA overlays (< 1 inch), chip seals, cape seals, and slurry seals. KYTC found that while the costs of these treatments were substantially less than a traditional HMA overlay, their service lives were only marginally shorter. As a result, the agency began increasing the use of these treatments on its secondary system. As part of developing its risk-based TAMP in 2018, KYTC evaluated life cycle strategies, as shown in Figure 4.3 Analysis of KYTC Future Costs Under Two Strategies that expanded the use of preventive maintenance overlays to its parkway and interstate pavements. The analysis results led the agency to select a life cycle management strategy that maximizes the use of preventive maintenance overlays on secondary roads and parkways and increases their use on interstate pavements over time. As shown in Figure 4.3, this new life cycle strategy achieved conditions over the 10-year TAMP analysis period that would have cost an additional $644 million if they had continued to rely on traditional 1- to 2-inch HMA overlays. By implementing these improved strategies, KYTC has significantly reduced the risk that the infrastructure will reach an unsustainable cost to maintain in the future.

Table 4.1 TAM Decision-Making Contexts
Key Questions and Connections to Other Chapters

	Strategic	Tactical	Operational
Key Decisions	Setting goals and objectives.	Capital investment prioritization and scoping and Integration of maintenance and renewal strategies	Delivery of the capital program, routine maintenance, and highway-operations activities.
Decision Makers	• Senior Leadership • Commission / Board • Legislature • External Partners	Directors and managers who are asset stewards.	District and field mangers, supervisors, and staff.
Key Questions	• What should our transportation system look like in the future? • How do we cater to the mobility needs of the future? • What should our focus and priority on infrastructure investment be? • With whom does decision making authority lie?	• How much money do we require to maintain our network? • Where and how should we allocate investment to maximize value for money? • What level of performance is acceptable for users for our transportation system, and what condition should we be targeting to support those service levels? • What criteria should be used to determine benefits for cross asset or cross program optimization?	• How should we deploy our resources (e.g. budget, staff, equipment, data) to ensure assets perform as expected and deliver reliable service? • Do we have effective programming, contract-development, and work management processes to deliver needed work on time with available resources? • How do we measure the impact of maintenance interventions on asset performance?
Other Factors	Decisions and outcomes of these strategic questions help focus investment. They add value to overall performance of the transportation system by setting priorities, values, and help prioritization of investment at lower levels. Creating new assets and disposing of existing ones are strongly influenced by decisions and priorities defined at this level. **Chapter 2** discusses these considerations in more detail, and the level of service section in this chapter discusses linking these strategic priorities to decision-making at lower levels. Performance and target setting in **Chapter 6** also discusses this linkage and how targets can be set to achieve these strategic goals.	This Chapter focuses on these questions and on the analysis that informs their corresponding answers and decisions. Life cycle management and analysis focuses on the existing transportation system and evaluates how: • How the asset is expected to deteriorate over time. • How the asset may fail prematurely. • How demands on the system are anticipated to change in the future. • What kind of interventions, investments could be selected. Asset Enhancement / Asset Acquisition / Creation of new infrastructure is also informed by LCCA, particularly through ensuring the entire life cycle cost associated with a new asset is considered during its planning. This sometimes requires a change in corporate culture and is discussed in **Chapter 3. Chapter 5** discusses how resource allocation is accomplished to balance investment needs to achieve.	Delivering a program work, ranging from maintenance activities to capital improvements, requires a coordinated management of a large workforce. It requires processes that minimize input of resources to get the output required for desired system performance. Work management systems, efficiency and improvement techniques and performance management focus on improving decisions at this level. These concepts are discussed in **Chapter 5, 6 and 7.**

Defining Asset Service and Performance Levels

Before asset performance can be managed, an agency must first define what it is seeking to achieve. In TAM, asset performance is most commonly defined in terms of asset condition or maintenance level of service. Performance may also be evaluated in terms of safety, availability, reliability, resiliency and other service attributes. Regardless of the method used to monitor performance, it should be used to inform analysis that supports decisions to help ensure that investments enable an agency to achieve its goals cost-effectively.

Establishing Desired Levels of Service

Before a whole-life strategy can be developed and implemented, an agency must determine what they seek to achieve. In many transportation agencies, the desired level of service (or asset management organizational objectives, in ISO 55000 terminology) provides the linkage between what the goals of an agency are, and what investments and interventions should take priority when managing assets. High level goals should directly influence investment choices when resource allocation decisions are made. Service levels help establish when gaps need closing to achieve a goal, and merits investment. Chapter 2 discusses ways to create linkages between goals and investment decision making.

When managing the life cycle of existing assets, performance targets are commonly established as a way to manage service levels for the transportation network. How to determine the expected level of performance may vary depending on the type of asset being managed. Level of service targets that are part of performance framework typically are a mixture of both customer focused performance measures, and technical service measures that help those responsible for the asset assess what types of interventions might be required and when. Customer focused service measures are important to road users and other stakeholders that require mobility. Travel time reliability, safety, load capacity and clearances, and lane availability are all examples of service targets that are customer focused. Condition, strength, regulatory compliance and examples of technical service attributes are commonly of greater interest to asset stewards than asset users. Both types are service level targets that are important to evaluate the efficacy, effectiveness and efficiency of a transportation system.

For pavements and bridges, and other assets managed using a condition-based approach, asset condition is commonly used to establish expected technical levels of performance, but also is relevant to customers. For example, condition is employed as a proxy in this way for pavements because it is objectively measurable, deterioration has some predictability. It is a valuable service attribute because often, user experience is also directly connected to condition as well. Potholes, rutting and roughness all reduce quality of service from a pavement. Performance measures, such as those discussed

TIP **"The organizational objectives provide the overarching context and direction to the organization's activities, including its asset management activities. The organizational objectives are generally produced from the organization's strategic level planning activities and are documented in an organizational plan." (ISO 55000, 2.5.3.4) These organizational objectives are analogous to strategic objectives typically found in long range transportation plans.**

in Chapter 6, are used to establish the desired long-term performance and to set short-term targets that can be used to track progress towards the long-term objectives. For other highway assets, including those managed using interval- or time-based maintenance approaches, performance may be linked to the expected service life, the ability of the asset to fulfill its intended function, and/or other operational factors. For these other highway assets, performance targets are often established as part of a Maintenance Quality Assurance (MQA) program in terms of desired maintenance levels of service (MLOS) and integrated with operational service targets that may also be customer focused.

Risk can also be used as a measure of performance. As described in chapter 2, risk considers both the potential impact and consequence of failure. This can be particularly useful when the potential consequences of failure impact other assets or facilities. An example of how Colorado uses risk to manage rockfalls is included in section 4.3 of this chapter. Additional details on how to track risk-based performance measures is included in Chapter 6.

Establishing a desired level of performance is typically a collaborative process that considers existing conditions, available funding, expected demands on the system, policy goals and guidance, and stakeholder priorities. The desired level of performance is typically established once baseline data is available, so performance trends can be evaluated. The desired level of performance may be adjusted over time to reflect changes in agency performance, changes in asset condition, capacity, safety, resiliency and other factors.

Practice Example
Maintenance Levels of Service

Colorado DOT

Each year, CDOT must report on departmental performance to its legislature, and a frequent topic is the condition and maintenance of highway infrastructure. The agency supports the annual maintenance portion of this report with its Maintenance Level of Service Measure, which rates the delivery of services in nine program areas in terms of a letter grade from A to D and F. The agency has used historic data to develop forecasted performance curves for each service area that estimate the resources needed to improve the maintenance level of service by a given amount over a specific time period. These estimates are summarized in a presentation to the legislature to report on current performance and expected performance given anticipated funding for each program area. The figure provides an example of information on MLOS in the 2016 Report. Once the targeted MLOS is established, maintenance funding can be allocated to ensure that agency priorities are met.

Maintenance Levels of Service by Program Area

Maintenance Program Area Description	Funding Needed for 'A' Rating	Budget FY2016-17 Funding	FY 2013-14 Budget	FY 2014-15 Actual	FY 2016-17 Projected
Planning, Training and Scheduling	$25.4M	$15.9M	C-	C	C-
Roadway Surfacing	$177.2M	$40.0M	B+	B+	C+
Roadside Facilities	$41.7M	$22.3M	A-	B+	C
Roadside Appearance	$12.7M	$8.6M	B	B-	C
Traffic Services	$109.5M	$67.7M	C+	C+	C-
Bridges & Structures	$122.0M	$12.2M	B-	C+	C
Snow & Ice	$88.5M	$73.5M	B	B	B
Service Equipment, Buildings & Grounds	$25.1M	$15.7M	C+	B-	C-
Tunnels	$9.8M	$6.2M	C+	B-	C+
US 36 (mtc. contract)		$1.2 M			
OVERALL MLOS	$611.9M	$262.6M	B-	B-	C+

Colorado DOT Example of Funding Needed to Support Maintenance Levels of Service.
Source: Colorado DOT. 2016. https://leg.colorado.gov/sites/default/files/cdot_smart_2017_presentation.1.pdf

Three types of service expectations are often used in combination to manage asset performance:

- **Performance target –** the level of performance beyond which additional performance gains are not desired or worth the additional cost. When performance is measured based on condition, the desired performance may describe the desired state of good repair. There may be an expected specific time frame to achieve this desires performance target.
- **Current Performance –** an intermediate level of performance achieved by the organization and is usually reported relative to the desired target. Target setting is described in more detail in Chapter 5.
- **Minimum acceptable performance –** the lowest level of performance allowed for the asset or asset class to still function as designed.

Performance expectations may be set for the road network, a road corridor, for individual assets or for a group of assets.

Commonly, performance expectations are set using a combination of asset class or subclass or sub network, such as:

- Key network corridors.
- Bridges on the National Highway System.
- Interstate pavements.
- Culverts larger than 10 feet in diameter.
- Traffic signals serving more than 10,000 vehicles per day.

The nature of performance expectations can be either strategic or tactical or operational. Strategic expectations support freight movement; for example, the long-term goal of providing unrestricted flow of legal loads is supported by a performance expectation of no load-posted or restricted bridges on interstate highways. This expectation cannot be accomplished without the tactical delivery of work to address factors contributing to the physical condition of bridges. Thus, an agency may include tactical expectations to perform maintenance and repair on structural members on a routine basis or as conditions warrant. These enhancements

Practice Example
Maintenance Levels of Service

Washington State DOT

When seeking to establish the connection between investments and performance across a wide range of assets or roadway attributes such as litter, vegetation height, drainage, or functionality it is helpful to relate all of the various measures of performance to a common rating scale. Washington State DOT has developed its Maintenance Accountability Process to establish the relationship between maintenance level of effort and the resulting level of service. The process rates conditions and services in seven areas using a common letter-grade system, or MLOS.

- Roadway Maintenance & Operations.
- Drainage Maintenance & Slope Repair.
- Roadside and Vegetation Management.
- Bridge & Urban Tunnel Maintenance and Operations.
- Snow & Ice Control Operations.
- Traffic Control Maintenance & Operations.
- Rest Area Operations.

Each group of services or conditions includes several performance measures, which are translated to the MLOS grades of “A” (highest performance), “B”, “C” (adequate performance), “D” or “F” (unacceptable performance). Applying the MLOS grades allows for a consistent means of rating performance across services and geographic regions. Letter grades can also be represented in photographs of facilities that meet the criteria for each condition state to support communications with stakeholder groups. The MLOS are outcome-based measures that allow the agency to predict the expected level of service that can be achieved based on anticipated budget and work planning decisions. By tracking maintenance expenditures and MLOS results annually, Washington State DOT is able to adjust its maintenance priorities and budgets to address system needs and stakeholder wants.

Source: https://www.wsdot.wa.gov/Maintenance/Accountability/

TIP A desired state of good repair is often established as the level of performance beyond which further performance gains are not necessary or desirable, usually represented as a condition state for a set of assets.

can be also integrated with renewal and other rehabilitation interventions to help improve both tactical performance metrics, as well as achieve higher level goals and objectives. Operational improvements such as more responsive snow clearance, and better signage are all integrated treatment options to achieve the strategic objective.

Life cycle management analysis, and the decisions it supports, require service levels, performance targets and other objectives to be able to determine the optimal choices for agencies to select during resource allocation. Over an asset life cycle, a range of interventions are possible, from reactive, routine and preventative maintenance, to large investment associated with renewal, replacement, or removal. Having targets helps select the right interventions and investment option while balancing risk, service and cost.

Connecting performance measures to higher level strategic goals also supports an agency's ability to communicate how technical measures relate to system performance as experienced by highway users and other external stakeholders, thus tying asset management outcomes to system performance. Asset management measures are often very technical. Performance indicators like bridge ratings, pavement distress measurements, and risk ratings are not commonly understood by those outside transportation agencies. However, agencies can use these technical measures to support the performance indicators that are more commonly understood and prioritized by system users and external stakeholders. Communicating system performance and the status of the road network is discussed in Chapter 2, and is illustrated in several examples below. Customer service level targets are often established for this purpose, and give users an ability to understand the quality of service they should expect on the transportation system.

Practice Example
Establishing Desired Maintenance Levels of Service

New Zealand

New Zealand's Local Government Act of 2002 requires councils to consult with their communities on their 10-year long-term plans (which includes a 30-year infrastructure strategy). To do this, councils must prepare a consultation document. The consultation document provides an effective basis for public participation in infrastructure decision-making associated with the long-term plan. It includes a fair representation of overall objectives, and how tax levels, debt, and levels of service might be affected by the intended plan and can be readily understood by interested or affected people. The Auditor General recently reviewed consultation documents produced by councils. Key findings highlighted aspects that help define good practice:

- Consultation documents present information in a concise, readable and understandable way.
- Clear and unambiguous explanations on why proposed taxation and debt increases and significant changes in plans or intentions were considered "affordable" or "equitable" make consultation documents more effective.
- Consultaton document present technical subjects in a relatable way, without over-simplifying the issues. For example, one council used a road-trip analogy to help make technical subjects easy to understand.
- Using a personalized approach helps connect with the readers. For example, one consultation document used two primary school children, Maia and Xander, who are pitched as the "champions of the Long Term Plan 2018-2038."

By focusing on the inclusion of transportation customers, New Zealand municipalities are better able to address customer needs, inform customers of the actions they are taking, and refine work planning practices to address concerns critical to infrastructure operations and customer expectations.

"We've been doing lots of tuning under the hood to keep costs low" (page 2)

"Stop! We're at a crossroads, a fork in the road; a decision needs to be made about how we proceed on our road trip into the future" (page 6)

"Our rates are similar to your car rego, where some of it is set, and some is variable depending on the type of car you have" (page 24)

How-to

Establish Customer-Based Service Level Targets

In many industries, service level agreements (SLA) are a common way for businesses and customers to understand the services being provided, the measures or key performance indicators (KPI) by which the service will be measured, and the level of performance that is expected for the price being paid. Homeowners may have SLAs for multiple services such as plumbing and heating, lawn care, or snow removal. In the public sector there is no formal SLA between the public agency that manages infrastructure and the individuals and groups who receive services from that infrastructure. However, many agencies find that establishing KPIs based on customer-needs and expectations is an effective way of informing budgetary, work planning, and capital programming processes to ensure that the agency's investments adequately serve system users. This How-to provides an overview of a process agencies can follow to establish KPIs and related performance targets based on customer, or stakeholder, input.

1. Define Stakeholders

The first step in establishing customer-based targets is to identify the customers. While customers are generally considered to be system users, there are many more individuals and groups concerned with transportation infrastructure than just those who use the transportation system. Figure 4.3 provides a list of typical stakeholders, but there are many more stakeholders than those listed.

2. Articulate what each stakeholder wants out of your transportation system

Each stakeholder has a unique set of wants with the transportation system. Most stakeholders have multiple requirements; however, the purpose of this step is not to assign all service requirements to the right stakeholder, it is only to be sure to capture all potentially relevant service requirements. This can be done through many different approaches such as: customer or industry surveys, direct meetings, or customer-feedback web or social media outreach. This effort should be as extensive as practical and updated frequently. While passive gathering of information is inexpensive, it may lead to over representation of some stakeholder groups and under representation of others. The agency's environmental justice policy or procedures can serve as a resource for engaging with groups that may otherwise be underrepresented.

Recruiting for TAM Roles

1. Define Stakeholders
2. Articulate what each stakeholder wants
3. How would you Measure their want
4. Which of those measures are most important
5. Establish service level statements and KPIs

How-to
Establish Customer-Based Service Level Targets

3. Determine how to measure or demonstrate that you are fulfilling the wants or desired services

Once the services desired by each stakeholder have been defined, the next step is to establish a means of measuring the delivery of those services. At times it may be possible to directly measure the service, but often that is not the case. Agencies sometimes use a standard to ensure a service requirement is met. Compliance with a standard becomes the performance measure. Other service attributes require measures that can be identified as a service target. These may change over time, given service level expectations and willingness to pay. Additional guidance on establishing performance measures can be found in NCHRP Report 551, *Performance Measures and Targets for Transportation Asset Management* and NCHRP Report 422, *Maintenance Quality Assurance Field Implementation Manual*.

4. Which of those potential measures are most important for investment decisions?

Determining which measures should be selected as KPIs is not a simple process and should be revisited regularly. It is best to focus on a few KPIs that are directly related to stakeholder needs or perception of performance than try to manage using a long list of measures. The more directly KPIs relate to the agency's business decision and stakeholders' understanding of performance, the better. For these reasons KPIs based on user experience such as congestion, safety, or freight movement can be advantageous. However, these may not relate directly to asset management metrics, which tend to be focussed on asset conditions.

There is also a need to choose KPIs which can be measured accurately and at the lowest expense. Using a prioritization matrix to rank potential KPIs based on their effectiveness in communicating stakeholder wants and ease or expense of reporting can be a good means of selecting the set of KPIs that will best serve the agency. Chapter 6 provides additional information on selecting performance measures and targets.

It is important to note that none of the criteria used to select are static. These criteria will change with time, so agencies should revisit their list of KPIs on a regular basis to make sure they are still the right measures, and there isn't a more cost-effective means of collecting the needed information. The process of updating KPIs should be documented in an agency procedure or policy.

Recruiting for TAM Roles

1. Determine the roles needed in the TAM program
2. Determine the competencies needed
3. Determine internal or external candidate
4. Develop a steering committee charter
5. Advertise and fill

5. Establish service level statements and KPIs for reporting to stakeholders

Service level statements can be derived from the resulting KPIS to address specific stakeholder wants. Using the example materials shown in figure 4.3, a resulting agency service level agreement might be:

The agency will provide a transportation network that:

- Is in good condition: (How Good? See Condition Target)
- Has sufficient capacity (How sufficient? See Travel Time Targets on commuter corridors)
- That is available to users 24/7 (How available? See Lane Closures measures)
- Is managed through responsible investment (How responsible? See our AMP and BCRs for all investments); while leveraging cost-staring opportunities with our partner stakeholders (See Cost Sharing Targets)

Figure 4.4. Example in support of establishing key priority indicators

Define Stakeholders	Stakeholder Primary Requirement	Potential Measures/Standards to meet stakeholder service requiremetns		Potential KPIs that influence capital investmenttt decisions	
		Standard	**Measure**	**Potential Service Level Reporting**	**KPIs, Priority given to projects that enhance**
Users					
Residents	Condition		Condition	State of Infrastructure	Condition
Commuters	Reliable travel time		Travel time / Flow rate data	Commute travel times	Travel time
Tourists	Clear signage for wayfinding	Sign Design Standards	% of network compliance	Annual Reporting/Trends	
School Buses	Wide shoulders/good sight distance	Road Design Standards	% of network compliance	Annual Reporting/Trends	
Service Provider Network Users					
Transit Providers	Reliable Travel Time for scheduling		Travel time / Flow rate data	Schedule On-Time rates	
Couriers and Freight Carriers	Bridge capacity and defined truck routes	Truck Routes	% bridge restrictions on truck routes	Annual Reporting/Trends	
Taxis	Available network 24/7		Lane closures rates	Annual Reporting/Trends	Availability
Regulatory Agencies					
FHWA	Compliance to standards		% of network compliance	Annual Reporting/Trends	Compliance
AASHTO	Compliance to standards		% of network compliance	Annual Reporting/Trends	
EPA	Compliance to standards		% of network compliance	Annual Reporting/Trends	
Wider Community					
Active Transportation Advocates	Bike lanes / paths	Bike route corridors	% designated network with bike lanes	Annual Reporting / Trends	
Agency Staff	Clear Objectives		Clear service levels / targets	AM Policy / AM Objectives	
Taxpayers	Getting value from investment	AMP, Decision Framework	Portfolio valuation, Benefit Cost Ratio	AM Plans / Valuation	Investment BCR
Neighbors					
Neighboring States	Good interconnectivity		% boundaries with constraints	Annual Reporting/Trends	
Metropolitan Planning Authorities	Cost sharing opportunities		% collaboration on potential projects	Annual Reporting/Trends	Cost shared

Developing Life Cycle Strategies

Most transportation infrastructure assets have long service lives, lasting years or decades. Making decisions based on short-term performance without an understanding of the long-term cost effectiveness usually leads to higher future costs. Through life cycle management, agencies can develop strategies for maximizing their ability to meet both short- and long-term goals with available resources.

Adopting life cycle management can often achieve desired performance levels at lower life cycle costs than traditional strategies. Improved performance comes from analyzing the impact of various sequences of treatments on the future performance and costs of an asset class or subclass. By comparing the costs and benefits of long-term sequences of treatments, agencies can develop life-cycle strategies which provide the best practical long-term performance at lowest practical long-term costs. The implementation of life cycle strategies also enables an agency to better address its stewardship responsibilities and improve the alignment between agency investments and priorities.

By establishing sound long-term strategies, agencies can minimize the life cycle costs of preserving assets, while also managing asset performance to a defined target, the extent practicable with available resources. While strategies with a short-term outlook may provide better short-term performance, they can greatly increase the risk of higher future costs.

Life cycle strategies in construction and design stages

Transportation infrastructure assets are expected to provide agencies with a desired level of performance over their design lives. To ensure the desired performance is achieved, decision-makers should consider factors that

Practice Example
Managing Long-Life Assets

When developing long-term strategies, it is important to differentiate between the primary asset, with a long service life, and elements or components of that asset, that may be repaired or replaced to allow the primary asset to achieve its design life. In the case of pavements, the pavement structure may require several wearing surface replacements, either through overlay or removal and replacement of the wearing surface, to ensure the pavement structure lasts as long as intended. For assets such as bridges or signal installations structural elements or functional components may be repaired or replaced multiple times within the service life of the primary asset. In almost every case failure to perform these maintenance and preservation actions, or failure to perform them at the appropriate time will lead to reduced service life of the primary asset.

When determining the appropriate treatment for a long-life asset, it is important to understand the root cause of the condition being prevented or corrected. Inexpensive treatments that address the visible or measured condition without addressing the cause of the distress are not cost effective. Examples of such treatments include:

- Thin overlays of asphalt pavements that are displaying structural cracking.
- Painting corroded structural steel members without proper surface preparation.
- Filling leaking bridge joints without proper materials or preparation.

While such treatments may, in some specific circumstances, be needed to provide minimal function or safety until a more substantial repair can be made, they should not be considered part of an optimal life cycle strategy.

Treatments made to achieve or extend the service life of these assets can also address changes in conditions or assumptions that have occurred since the asset was designed and constructed. Examples of these types of treatments include seismic retrofitting or applying scour protection to bridges, or increasing the hydraulic capacity of corrugated culverts by relining with smooth interiors. Each of these treatments reduces the risk of premature failure to an extreme event, and may at the same time address other structural or functional needs, without replacing the primary asset or changing its functional nature, i.e. increasing traffic-carrying capacity.

impact asset service life and future costs at the time of construction. This is commonly performed as part of the project development process to select a preferred design alternative. Factors to forecast should include design criteria, constraints, standards, and risks.

- Traffic
- Environmental and climatic conditions
- Material properties
- Design standards
- Operational constraints
- Construction practices
- Climate change
- Changing customer expectations
- Regional, state and national travel pattern changes
- Advancing technology

Because these factors contribute to asset performance, deterioration and the continued functionality of the asset, they must be considered when developing life cycle strategies in early and later stages of asset life. Life cycle strategies are based on an understanding of how these factors contribute to the rates of deterioration, how well the asset will accommodate future requirements and which treatments are effective in addressing deterioration or slowing the rate at which the asset deteriorates or underperforms.

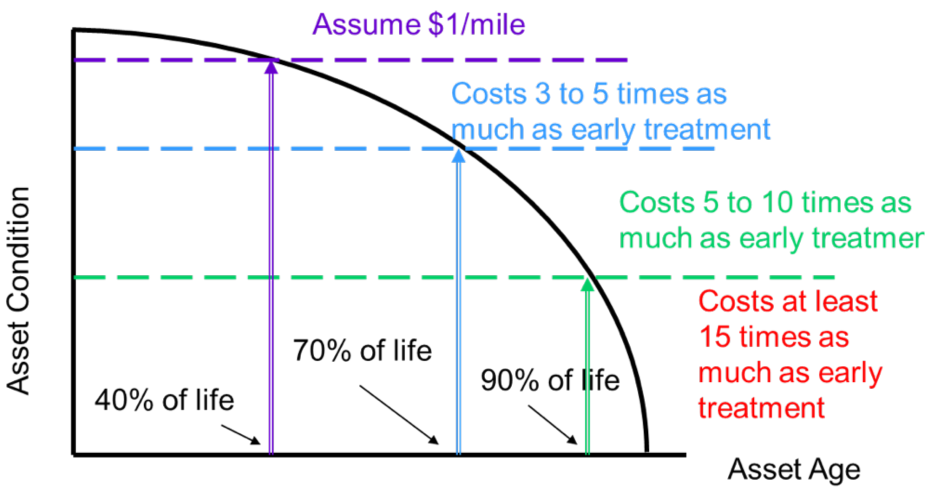
Operation, maintenance, and rehabilitation strategies

Treatment strategies consider how the asset, once constructed, will be managed to ensure it attains its design life, while maintaining the desired level of functionality. Special consideration should be given to long-life assets. There are three primary reasons short-term strategies are inefficient for long-life assets:

- As long-life assets age, deterioration accelerates, and there is greater risk of performance failing to meet current needs.
- As deterioration increases, the cost of treatments addressing deterioration tend to increase exponentially.
- Inexpensive treatments that restore condition but do not address the root cause of the deterioration will fail prematurely, leading to higher future costs.

These factors are reflected in Figure 4.5, which illustrates these concepts using a generic asset deterioration model. As shown in the figure, the average cost of treatment increases substantially as assets age. Additionally, the rate of deterioration tends to accelerate as assets age. Long-term strategies that use low-cost treatments early in an asset's life cycle tend to improve asset condition very cost-effectively by deferring the need for most costly repairs.

Figure 4.5 Example Showing the Cost of Deferred Treatments



Practice Example
Use of Incremental Benefit Cost to Demonstrate Long-Term Benefits

South Dakota DOT

To analyze the benefits of potential actions at the network level, South Dakota DOT (SDDOT) uses incremental benefit cost (IBC) analysis and deterioration models to determine the combination of feasible reconstruction, rehabilitation, and preventative maintenance treatments and timing at the network level that will give the best overall pavement and bridge conditions at the lowest practicable life cycle cost.

IBC analysis is used to answer a series of two important questions regarding pavement section treatments: Should the section be improved now, and if so, what is the best improvement to make? SDDOT's IBC analysis process answers this set of questions by determining the combination of feasible reconstruction, rehabilitation and preventative maintenance treatments and timings that will use the anticipated state funds to yield the optimal overall asset conditions on the state highway network over a 20-year analysis period and the best long-term value to the system users (SDDOT TAMP, 2018).

Considering Transformational Changes in Life Cycle Management

Life cycle management requires an understanding of past performance to predict future performance and plan appropriate actions. However, as technology advances and society's needs change, the inputs and objectives of life cycle management need to adapt. Technology can lead to new materials or techniques that allow agencies to get longer life from existing assets. However, technology can also lead to broader societal changes that may make the need for some assets obsolete. Similarly changes in standards and regulations, may make it necessary to replace or update some assets prior to the planned ends of their service lives. Asset managers should regularly review their assumptions about anticipated asset service lives, consider new treatment options, and adjust to technological and regulatory trends and adjust the life cycle approach accordingly. Much of the information to support this effort can be found in agency's long-term planning documents, as discussed in Chapter 2.

Incorporating Resilience in Life Cycle Strategies

Environmental changes such as extreme weather, temperature rise, sea level change, and changes in other environmental conditions can threaten transportation infrastructure. Even when these changes don't increase the risk of failure, they can require infrastructure owners to change their strategies for managing assets. This is particularly important for long-life infrastructure assets such as bridges, pavement, culverts, and geotechnical assets.

Resilience is the term used to describe an asset's ability to withstand environmental changes. Resilience can be considered at all stages of an asset's life and should be an integral aspect of any life-cycle strategy.

FHWA developed the Adaptation Decision-Making Assessment Process (ADAP) as a tool for planners and designers to address resilience in the design of infrastructure projects. While ADAP was developed to be used on a project-by-project basis, it can also be applied to the development of a lifecycle strategy. Figure 4.6 shows the 11 step ADAP

Practice Example
Using Root Cause Analysis and Improving Asset Performance

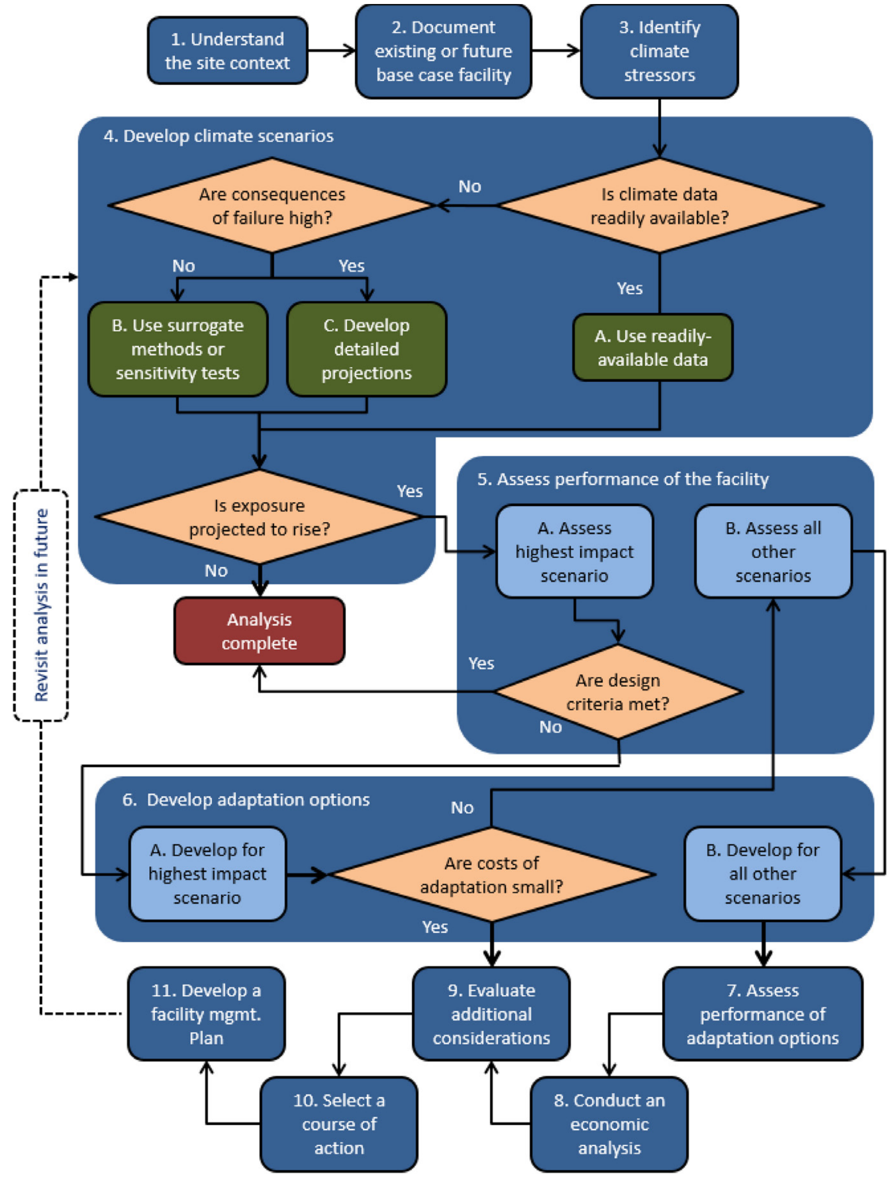
New York State DOT

In 1994, New York State DOT (NYSDOT) determined that it needed to modernize its bridge designs to have longer service lives to help reduce future rehabilitation and replacement costs. Prior to this effort, the agency designed bridge decks to for a 50-year service life with a planned rehabilitation at year 35. The goal for this effort was to double the bridge deck design life to 100 years with a planned rehabilitation at year 75. The NYSDOT Materials Bureau investigated the major causes of bridge deck deterioration and determined that the primary cause of failure was corrosion of the reinforcing steel due the intrusion of chlorides from winter maintenance activities. Upon further investigation, it was determined that the chlorides were penetrating the bridge decks both through cracks and the natural porosity of the concrete. As a result of this research, the agency began a research and development effort to design a new standard concrete mix design that had lower permeability, higher resistance to cracking, and was pumpable to support standard bridge deck construction practices.

The result of the Materials Bureau's effort became NYSDOT's "Class HP" concrete, which utilizes fly ash (a byproduct of electric power production) and micro silica (a byproduct of electric arc furnaces used in manufacturing) to replace some of the Portland cement in its standard bridge deck concrete. These new materials are finer in size than cement particles, resulting in well graded denser packing of particles in the concrete, which reduces permeability. Class HP also creates less heat while it cures (or hardens), which reduces the occurrence of thermal shrinkage cracks when the deck cools. In 1997, Class HP became NYSDOT's standard concrete mix for bridge decks. By using a failure mode analysis to identify the primary causes for bridge deck deterioration, NYSDOT could use new materials technology to address those causes and significantly lengthen the design life of its bridge decks.

process. The key difference between applying the ADAP process to developing a life-cycle strategy, as compared to a project, is in step 1. Understand the site context. When applied to a project this step is focused on a specific physical location, bounded by the project limits. When applied to developing a life-cycle strategy, the site context will likely be broader to an area that is expected to be subject to a given environmental change, such as increasing seasonal temperatures, or sea level rise. Once the proper context is established, the process steps can be followed to evaluate potential strategic adjustments that will allow life cycle management practices to account for the anticipated effects of the environmental change.

Figure 4.6 Decision Tree of the ADAP Steps



Source: FHWA. 2016. TEACR Engineering Assessment. Adaptation Decision-Making Assessment Process (ADAP). FHWA-HEP-17-004

Practice Example
Developing a Resilient Life Cycle Strategy for Pavements

Maine DOT

Maine is a cold-weather state with soils that are susceptible to severe frost conditions during winter months. In cooperation with FWHA and its Transportation Engineering Approaches to Climate Resiliency (TEACR) effort, Maine DOT undertook a project to assess the impacts of changing climate on the performance of pavements and develop strategies to offset those changes. The study looked at anticipated changes in both temperature and precipitation over the course of the 21st century. The study followed the ADAP process as shown in figure 4.6. The study indicated that anticipated climatic changes will lead to moderate changes in pavement performance. The study identified both engineering and operational adjustments Maine DOT can adopt to address these changes. The full report can be found on FHWA's website at: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/me_freeze_thaw/

Section 4.2

Common Life Cycle Management Approaches for Transportation Assets

All infrastructure assets are designed to have a certain functional service life. However, there are major differences in how assets deteriorate (physically or in performance), the available treatment options to address deterioration, and different levels of consequence in terms of operational performance that arise, if deterioration is not addressed. In selecting a life cycle management approach for an asset-class or sub-class, an agency must understand asset deterioration, performance, and risk over time and determine what decisions need to be made throughout the asset's service life to ensure that the asset is managed effectively. In turn, the management strategies affect the supporting data that must be collected and analyzed.

There are many different criteria that can be used to manage assets and establish life cycle strategies. Performance can be measured in many ways, but with transportation infrastructure, asset condition is typically used either as the measure of performance, or as the measure of an asset's ability to provide the desired function, for example, carry the designed traffic capacity safely under design conditions. Additional information on performance management and performance criteria is provided in Chapter 6.

Depending on the criteria for performance, the available performance data, and the risk of asset failure, agencies will typically choose a standard approach to establishing a life cycle strategy for a given class or subclass of assets. Life cycle strategies describe the types of actions to be applied to an asset throughout its service life, including activities such as maintenance, preservation, and rehabilitation. This section describes how life cycle management is applied to transportation infrastructure assets to assist in selecting an effective approach for any class of assets. This section has two parts:

1. **Life Cycle Management Approaches.** Several approaches are available to agencies for managing assets throughout their life cycle. These approaches differ in the events, or situations that trigger work, the practices or analyses used to identify those triggers, and the data needed to support the approach.
2. **Determining the Most Appropriate Life Cycle Management Approach.** Agencies can select an approach to life cycle management for each asset based on how the actions that can be taken to prevent or correct deterioration, and the consequences of asset failure.

Life Cycle Management Approaches

Different types of assets require different management approaches to operate effectively and provide the expected level of service. This section introduces common management approaches used by transportation agencies to appropriately manage asset service life at both a network and asset level.

Virtually all transportation infrastructure assets are designed to have long service lives, lasting years or even decades. This means life cycle management must include long-term predictions that come with inherent uncertainty. Further complicating matters, the condition or performance of some assets may be difficult, expensive, or impossible to discern. This is most common with geotechnical assets or hidden elements on complex structures. Addressing this uncertainty requires integration with the agency's risk management practices, and consultation with technical experts, such as hydraulics and geotechnical engineers. Risk management practices are discussed in more detail in Chapter 5. This section highlights how uncertainty should be considered when selecting a management strategy to maximize service life and address risk.

Condition-Based Management

A condition-based management approach is the life cycle management approach that is the most commonly associated with asset management at U.S. transportation agencies. In condition-based management the condition of an asset is measured, and used to forecast and identify the onset of failure. Maintenance and preservation activities are identified to address the failure and restore or extend service life. While the objective of asset management is to support the reliable performance of the asset, the performance measures most commonly used for physical assets are condition-based. Agencies that are very advanced in their asset management practices may be able to apply the condition-based management approach to other aspects of asset performance.

Condition-based management relies on the collection and analysis of asset condition and defect data. This data is then used to understand the current state of individual assets and when aggregated is used to predict the future condition state of similar asset types. When linked with intervention data and condition threshold information, the future impact of potential actions can be assessed, all with the view of optimizing an asset's service life cost-effectively. Accordingly, a condition-based management approach combines condition monitoring with performance predictions and knowledge of preventive or restorative actions, to establish a cost-effective life cycle plan. The condition-based management approach can be applied to simple and complex assets, groups of single assets or a whole network. In a network perspective, components could be individual assets such as pavement segments and bridges and at a project level, components could be elements of individual assets.

Interval-Based Management (Age Based)

Interval-based Management is most commonly applied to operations assets (striping, signs, guardrail), where just an inventory is maintained. Condition assessments may not be financially feasible or practical. Additionally, these assets are often related to compliance, meaning their condition state either meets a specific standard, or does not. With interval-based management, asset performance data or manufacturer's suggested life estimates are used to establish a time interval representative of the service life beyond which the cost of asset failure outweighs the cost of replacement. The service life being the average life that all assets or components of a type are expected to last. Cyclically applied interventions can also be classed as interval-based management strategies, as there is fixed period between a set of predefined actions that have to be taken. An interval-based approach is most commonly applied to manufactured assets with highly uniform performance levels. It is less applicable to assets constructed on site or long-lived complex assets where there is a greater level of uncertainty surrounding the expected life of the asset. Examples of the types of assets that are often maintained on an interval-based approach are signals, ITS equipment, and other mechanical and electrical related items.

Reactive Management

Reactive management unlike condition or interval maintenance does not use forecasting to understand the likely timing of an intervention. Accordingly, reactive management excludes all or most actions to address asset condition or performance, until the asset reaches an unacceptable condition state. The condition state may be influenced by accumulated deterioration or a specific event, like a crash or intense storm. Reactive-management is commonly applied to low-value or less critical assets, redundant assets, or assets for which failure represents an acceptable risk. To create a reactive-based management strategy, minimum acceptable condition thresholds, must be defined. Reactive management strategies often require an agency to have a mechanism to deliver required work within a specified time frame, to avoid unacceptable levels of risk. This may include properly staffed and equipped in-house maintenance forces or "stand-by" contracts, so work can be dispatched and delivered quickly. Examples of assets managed using a reactive-based approach include fences, brush, lighting, raised pavement markers, impact attenuators, and rockfall.

Practice Example
Overhead Sign Structures – Condition-Based Management

Indiana DOT

Overhead sign structures are critical to safe and effective highway performance since they support signs, cameras, sensors and other equipment in support of routine and emergency operations. These structures typically have long service lives, but failure risk exists if they are not maintained. Indiana DOT found that failure to their overhead sign structures could be effectively mitigated through routine, real time condition monitoring and condition forecasting for predicting failure. Therefore, the Indiana DOT uses a condition-based approach for maintaining its overhead sign structures.

Indiana DOT's condition-based maintenance approach involves the steps listed below to ensure the overhead sign is installed corrected, material specifications are met, and the connection to the ground is secure:

- Professional engineers perform inspections
- An asset inspection report is developed
- The asset inspection reports are submitted to the districts
- The districts review the reports and prioritize work activities
- Work orders are developed to address the highest-priority needs
- In-house crews or local contractors perform the work

As a result of the DOT's condition-based maintenance approach, the department realized an increase in the amount of collaboration between districts and an improvement in how overhead sign structure repairs and replacements are monitored and prioritized.

Source: FHWA (2019). *Handbook for Including Ancillary Asses in Transportation Asset Management Programs* (pending publication in 2019).

Selecting the Right Management Approach

The selection of a management approach considers the mechanisms that lead assets to fail to provide their required or desired service, the consequences of failure, available intervention options and related costs.

Factors for Comparing Life Cycle Management Approaches

Failing to achieve a service level target requires an intervention, or reassessment of the reasonableness of the target. If improvement is required, selecting a management strategy is a function of where performance is insufficient. Safety improvements can reduce crash rates, additional lane capacity can improve travel time reliability, operational enhancements can improve emergency response rates and road availability during inclement weather. Where condition is below target, at a network or corridor level, interventions may be required in multiple areas.

Selecting interventions to achieve condition targets for an asset class or subclass is a data-driven, risk-based process. It evaluates what circumstances lead to asset failure, the subsequent consequences of failure, the options available to avoid failure and their costs. Costs should include the cost to monitor/analyze/ manage an asset in addition to the cost to repair. Based on an understanding of these factors, an agency can determine what strategy will be the most appropriate. The three management strategies introduced in the previous section are incorporated into Table 4.2 along with summaries of the various factors used to compare the approaches.

Reliability Centered Maintenance

Several of the principles described in this section are based on a Reliability Centered Maintenance (RCM) approach, a technique that is sometimes used by an agency to identify the most appropriate management method. Looking at an asset or asset class from an RCM perspective helps to select a management approach based on safety, operational and economic criteria. RCM is commonly applied to complicated assets that may require a range of management approaches for different components of the asset.

The RCM process has its roots in the aviation industry related to the mechanical components of aircrafts, but has been adopted across multiple industries for mechanical, electrical and infrastructure assets. Within the highways industry RCM has been considered for ITS assets. More information on the use of RCM for ITS assets has been published by Austroads (2016): Reliability-centered Maintenance Strategy and Framework for Management of Intelligent Transport System Assets.

RCM considers seven fundamental questions to select the most appropriate management approach for a set or type of assets (SAE International 2009). These questions can be applied to the selection of life cycle management approach. Based on

The term Reliability Centered Maintenance is defined by SAE International. While the use of the term maintenance in this instance does not align with use of the term in the remainder of this guide, it is used here to avoid confusion in regards to the title of the published standard.

Table 4.2 Comparison of Management Strategy Approaches. Adapted from SAE International 2009

Management Approach	Condition-Based	Interval-Based	Reactive-Based
Decision Making (Intervention) Approach	Selects intervention based on a forecasted condition exceedance interval.	Asset is treated based on a time or usage basis whether it needs it or not.	Treatment is performed to fix a problem after it has occurred.
Data Needs	Inventory information (Asset / Component) Historical condition and expert data – deterioration curves Current condition and defect data Historical Intervention and cost data – intervention strategies. Asset / component type and material data Intervention thresholds for condition	Inventory information (Asset / Component) Asset / component age. Remaining useful life of asset / component. Timing and type of last action. Interrelationships of different interventions, and how they affect the selection and timing of down-stream actions	Inventory information (Asset / Component) Current Condition data. Intervention thresholds for condition. Historical cost data
Life cycle Planning Expectations	Require the ability to understand the effects of different funding strategies. Wish to forecast the future condition state of the network or specific asset classes. Wish to minimize the life cycle cost.	Wish to gain an understanding of the typical average cost to manage the network or specific asset classes	General costs estimates based on experience. Limited need to actively manage the asset.
Considerations	Cost of collecting and analyzing condition information and developing forecasting models.	Diminished cost effectiveness / efficiency compared to condition modelling. Does not support knowledge development of asset behavior (inhibiting the move to more cost-effective regimes).	Often considered immature but is appropriate for assets if only minor consequences occur from a service disruption.
Typical Usage cases	High risk / criticality assets or risk must be more actively managed. Large portfolios or high value assets of similar construction forms Scenario planning is required Long-lived assets that can have numerous management approaches applied to them. More advanced asset management planning is required Cost uncertainty over time must be assessed (stochastics modelling)	Moderate or low risk assets. Mandated manufactures management regimes or Short-lived assets Buried assets where condition data is hard to obtain. Assets where the cost to collect condition data is expensive relative to the maintenance activity that is required	Low risk or criticality assets. Assets where the effects of accumulated defects are not critical to their functionality. Assets that are likely to be subject to unforeseen events or impairment e.g. barriers or light poles.

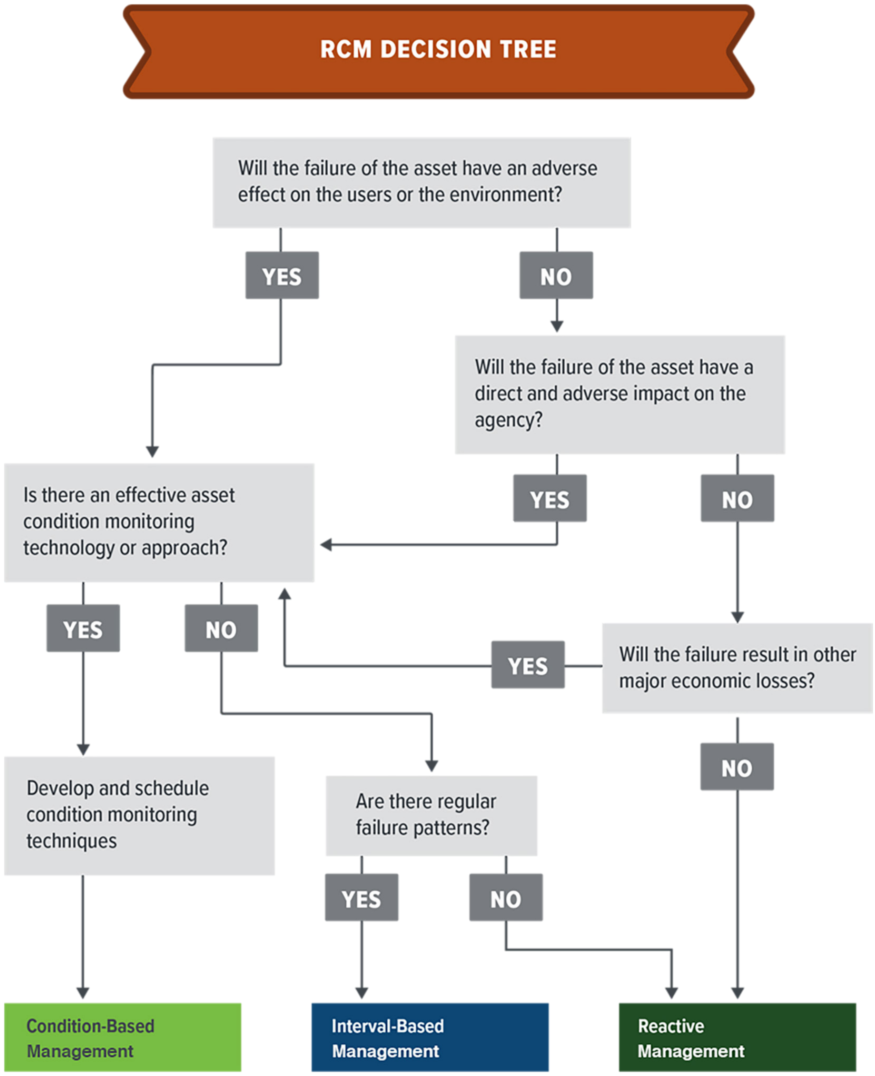
Source: Adapted from SAE International. 2009. *Evaluation Criteria for Reliability-Centered Maintenance Processes.*

the responses to these questions, an agency can determine what maintenance approach, for which parts of the asset, will maximize the likelihood of an asset performing its desired function for the lowest practicable cost. These questions are as follows:

- What is the item supposed to do and what are its associated performance standards?
- In what way can the asset fail to provide the required functions?
- What are the events that cause each failure?
- What happens when each failure occurs?
- In what way does each failure matter?
- What systematic task can be performed proactively to prevent or diminish to a satisfactory degree the consequences of the failure?
- What must be done if a suitable preventive task cannot be found?

RCM can be presented in a decision tree to aid agencies in selecting the best management approach. Agencies can also customize the questions and decision tree to meet their specific need. Figure 4.7 represents a portion of a decision tree customized to select the appropriate management approach for ancillary highway assets. By applying these questions to an asset class, an agency can prioritize asset classes for monitoring and active management. An agency can also determine which assets present limited risks to system performance and can be managed through less expensive means.

Figure 4.7 Maintenance approach decision tree



Source: FHWA. 2020. *Prioritizing Assets for Inclusion in Transportation Asset Management (TAM) Programs.*

Section 4.3

Managing Assets Over Their Life Cycles

This section provides guidance on applying the appropriate management approach to develop life cycle strategies. The management approaches introduced in the prior section each require different practices, tools, and data to implement.

This section has three parts:

1. **Managing Assets Using Condition Based Management.** Applying a condition-based approach requires quality data to support performance modeling. Models need to reliably forecast future conditions so appropriate actions can be planned and delivered at the right time.

2. **Managing Assets Using Other Management Approaches.** Many asset classes do not require the complexity of condition-based management. However, alternative approaches have their own requirements to ensure the desired level of service is reliably provided.

3. **Implementing Life Cycle Management.** Implementing new asset management practices and tools requires organizational, procedural, and policy changes. This section builds on material in chapter 2 to discuss specific steps encouraged for successful implementation of life cycle management.

Managing Assets Using Condition Based Management

The condition-based management is the most complex of the approaches introduced in Section 4.2 and requires a commitment to the collection of reliable inventory and condition information over an extended period and the of condition models to predict future deterioration to evaluate the type and timing of various treatment actions in terms of risk and performance.

Using Computerized Management Systems to Optimize Life Cycle Management

For condition-based analysis, computerized management systems are valuable tools for evaluating life cycle strategies. Computerized systems support the larger life cycle management process by providing relevant, reliable information and analysis results to decision makers at the right time.

Condition-based management is common for pavement and bridge assets. Often pavement and bridge decision making is supported by a computerized system that is used to support optimized life cycle management. The results from this analysis provide insights into optimal life cycle strategies for all network assets or for a specific group of assets. These models can be configured to include the effects, maintenance, preservation, rehabilitation, and reconstruction actions. Depending on the type of condition-based modeling approach, uncertainty can also be included.

Various life cycle scenarios can be generated by modifying one or more variables in the analysis. By running multiple network-level scenarios and comparing the results, pavement and bridge management systems can identify viable life cycle strategies and help an agency select the strategy that best achieves the stated objectives.

More information on the use of pavement and bridge management systems is available in the FHWA document, *Using a Life Cycle Planning Process to Support Asset Management: A Handbook on Putting the Federal Guidance into Practice*. Life cycle planning is a required component of risk-based TAMPs developed by state DOTs (23 CFR 515), that uses computerized asset management systems to establish long-term life cycle strategies for pavements, bridges and other highway assets. NCHRP Report 866, *Return on Investment in Transportation Asset Management Systems and Practices*, provides an assessment of how state DOTs have implemented asset management systems, including practice examples. The end of this section includes a how-to guide for using a pavement management system for life cycle planning, a requirement for risk-based TAMPs developed by state DOT's for pavements and bridges on the National Highway System (23 CFR 515).

These computerized systems are designed to develop network-level scenarios for analyzing the impacts of different program variables over long periods of time. Typical pavement management scenarios will cover 10 to 40 years, while bridge management scenarios may need to cover 100 years or more to ensure inclusion of multiple life cycles within the scenario.

Various life cycle scenarios can be generated by modifying one or more variables in the analysis. By running multiple network-level scenarios and

Long Term Analyses

It is good practice to run forecasting analyses for a time period 1.5 to 2 times longer than the time period of interest. Doing so provides long-term context to the analysis results in the last year of interest. Without extending the analysis beyond the timeframe of interest, decisions made in the final year may introduce risks or trends in subsequent years that would be unknown to the decision makers. Because life cycle management includes the full asset life cycle, it is recommended that these analyses are run beyond at least to the point of a recommended reconstruction for an asset that is new in year 1 of the analysis.

Practice Example
Use of a Pavement Management System to Establish a Life Cycle Strategies

Ohio DOT

As required under MAP-21, Ohio DOT conducted a risk assessment to identify the most significant threats and opportunities to its pavements and bridges. The analysis revealed that anticipated flat revenues, combined with the annual increases in cost to pave roads and replace bridges, would lead to significant reduction in conditions without changes to existing practice. The potential deterioration in pavement and bridge conditions were expected to significantly increase future investment needs due to the increase in substantial repairs that would be required.

Following the risk assessment, a life cycle analysis was conducted. The analysis found that by focusing on the increased use of chip seals and other preventive maintenance treatments on portions of the pavement network, the annual cost of maintaining the network could be reduced. A life cycle analysis for bridges showed similar results. The bridge analysis found that with just 5 percent of the NHS bridges receiving a preservation treatment annually, the DOT could reallocate $50 million each year to other priorities. The investment strategies outlined in the TAMP and the changes made to the DOT's existing business processes enabled the agency to offset the potential negative impact of the anticipated flattened revenue projections.

The differences in the adopted life cycle strategies are compared to the past strategies in the Figure. Although the total number of treatments applied over the analysis period increases, the annual life cycle cost decreases because of the reduction in the number of rehabilitation strategies needed.

Ohio DOT's Pavement Preservation Strategy Comparisons
Source: *Ohio DOT Transportation Asset Management Plan.* 2018. http://www.dot.state.oh.us/AssetManagement/Documents/ODOT_TAMP.pdf

comparing results, pavement and bridge management systems can identify viable life cycle strategies and help an agency select a strategy that best achieves the stated objectives.

Predicting Asset Performance

A life cycle strategy is enhanced by the availability of models and analysis tools that facilitate the evaluation of different combinations of treatment type and timing across the asset class. For this analysis a model that predicts future asset deterioration and response to treatments is required.

For condition-based approaches to managing assets, historical performance is typically used as a baseline for developing models to predict future performance. The predicted conditions are used to determine the type of treatments that may be needed over an asset's service life, so the ability to accurately predict asset conditions in the future, with and without treatment, is an essential component of asset management. Models are developed by comparing performance, typically measured as asset condition, over time with actions or treatments performed on specific assets. This means that performance is associated to the last action or treatment that impacted performance in a positive way. However, assets may also receive treatments that delay the onset or advancement of distress. As a result, most models assume assets receive some level of preventive or routine maintenance between more significant treatments. If agency practices change to delay or cease maintenance activities, assets may not perform as models predict.

Several methods can be used to estimate future asset performance, the two most common of which, deterministic and probabilistic, are described below. Additional information has been published by NCHRP (Report 713, 2012): *Estimating Life Expectancies of Highway Assets*. This report also contains guidance on selecting the most appropriate modeling approach for various highway asset classes.

Deterministic Modeling

Deterministic modeling is a common and relatively simple approach for using historic data to predict future asset performance. Deterministic models apply regression analysis to one or more independent variables, typically condition over time, and develop a "best-fit" equation to determine the rate at which asset conditions change. The independent variables are used to predict a single dependent variable, most commonly represented as the predicted condition at some point in time in asset management applications. Developing deterministic models is relatively easy but relies on quality data collected consistently over several years to produce dependable results. Deterministic models are more easily implemented as they are more readily paired with linear program solving. They also provide consistent outputs. The downside of deterministic models is the limited insight that they provide into the cost uncertainty surrounding a strategy.

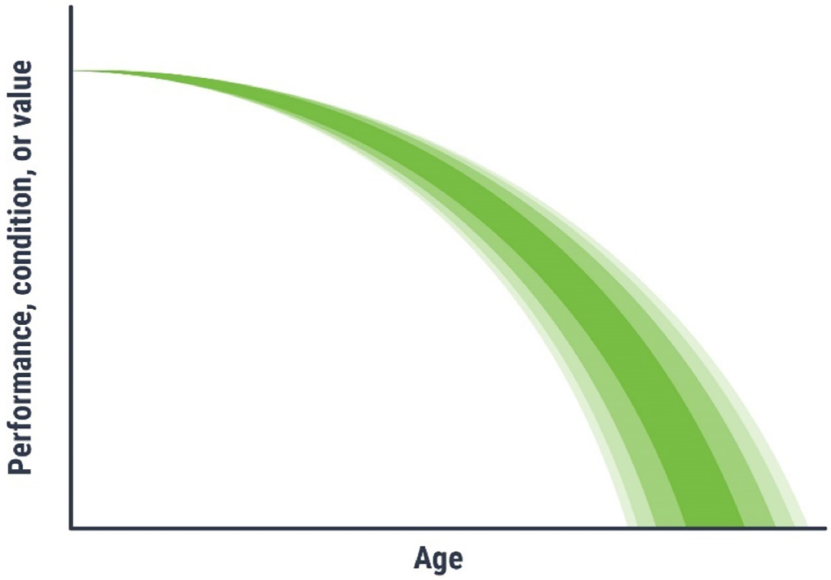
Probabilistic Modeling

Unlike deterministic models, which provide a single repeatable outcome, probabilistic models provide a distribution of possible strategies that provides insight into the cost uncertainty of plans. Probabilistic models can also more readily accept uncertainty in other variables, as represented by the shading in Figure 4.8. Given that condition changes are probabilistic, no two strategies that the model will provide are the same. This means that multiple iterations of the model with the same inputs can provide different results. Accordingly, probabilistic models are useful for setting funding limit expectations, while deterministic models help to provide insights into which projects are best to apply to specific assets.

Common approaches to developing probabilistic models are the Markov, Semi-Markov and Weibull models. Markov modeling works well for assets with condition ratings based on regular inspections. There are several ways of establishing a Markov model, but the simplest is to calculate the proportion of assets that change from one condition state to the next in any given year. These proportions are then used to develop what is known as the transition matrix. At the start of the model run, an asset "knows" its condition state. Once this is known there is then a probability it will change from its current condition state to the next in any given year. While these types of Markov approaches have been widely used, they do not necessarily model deterioration effectively, as the rate of change of condition increases with time. To address this, Semi-Markov models are used. Like Markov, Semi-Markov models have a condition transition matrix, but this is also augmented with a time selection matrix. In these models the probability of a condition jump is calculated, then the length of time an asset will remain in that condition state is also selected. Using more advanced mathematical techniques, the Semi-Markov approach can be expressed similarly to the Markov approach, but for Semi-Markov, the transition matrix changes with time. This reflects the increasing likelihood the asset will transition (deteriorate faster as its ages). Such models are typically used on long-lived assets.

A Weibull model offers another approach for modeling asset deterioration. A Weibull distribution predicts the likelihood of asset failure or deterioration as a function of age. Weibull models are particularly useful for addressing assets rated on a pass/fail basis during inspection. The Weibull model provides an additional factor meant to address the increasing or decreasing likelihood of an asset moving from an acceptable to an unacceptable state between inspection cycles. Reliability is the inverse of the probability of failure (i.e. 1 -p(f)). Reliability, like Weibull can thus be used to assess the likelihood an asset will provide the required service. The relationship between time and reliability is assessed by analyzing asset behavior to understand potential modes of failure. This analysis is a core aspect of reliability-centered maintenance, and is more typically used on short lived assets.

Figure 4.8 Example of a probabilistic model.



Source: Adapted from Transportation Research Board. 2012. *Estimating Life Expectancies of Highway Assets, Volume 1: Guidebook*. https://doi.org/10.17226/22782.

Accounting for Uncertainty in Asset Performance

Performance modeling uses historic data to estimate future performance; however, not all future events are predictable nor is past performance necessarily a predictor of future performance. This section considers the how uncertainty can be introduced into the analysis.

The unpredictability of future events introduces uncertainty into prediction models. Additionally, the amount of uncertainty tends to increase with time so their affects are compounded. As outlined in the previous section, probabilistic modeling is one approach that can be used for accounting for uncertainty, but what level of uncertainty is acceptable?

To minimize uncertainty, an agency must first understand the source of the uncertainty. A common type of uncertainty related to asset management is the behavior of the assets themselves. Due to the advancement of technology and knowledge and differences in materials and construction practices, there can be significant differences in performance between otherwise similar assets. The change in behavior can be positive, such as the introduction of epoxy-coated reinforced steel in bridge decks to delay the onset of corrosion from road salt intrusion or the introduction of Superpave and performance graded asphalt binders to reduce pavement cracking and rutting. Other changes in behavior are less easy to predict, such as the impact of salt intrusion on prestressed, post-tensioned concrete box-beam bridges. Other sources of uncertainty include:

- Weather events, e.g. flooding, drought, or freeze-thaw
- Earthquakes
- Climate change
- Traffic accidents
- Data inaccuracies
- Inaccurate models
- Poor assumptions

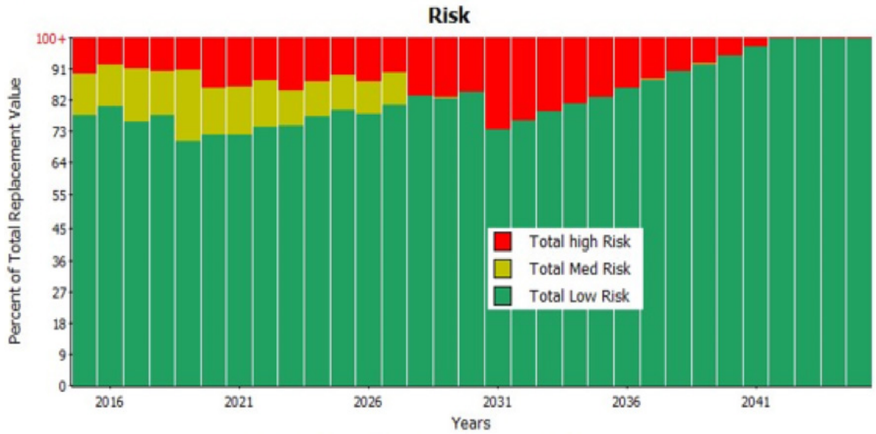
Practice Example
Deterministic Modeling of Culvert Condition

Halifax Regional Water Commission

Halifax Regional Water Commission (Halifax Water) has employed a deterministic modelling approach to create a plan for their storm water assets. The management system was used for long-term planning their culvert portfolio (approximately 1744 cross culverts on 3700 lane km of regional roads). The software uses deterioration curves, a temporal model periodic simulation model and has integrated Geographic Information System (GIS) capabilities. Initially the analytical objective of the model was to maximize the average condition of all the culverts and minimize the investment. Several constraints were embedded within the initial model analysis including:

- Non-Increasing percentage of culverts in critical condition
- Replace all culverts that exceed expected useful life
- Budget not to exceed scenario

The scenario analysis allowed Halifax Water to establish a minimum investment level required to bring the portfolio to an acceptable average condition state, have a reliable forecast of future condition trends, and quantify an estimate of accepted risk of failures. The figure below shows the agency's forecasted risk of failure over time based on the selected strategy and projected funding.



NBDTI forecasted culvert conditions using a deterministic model.

Uncertainty caused by variability in the data can often be addressed through the development of quality assurance plans that describe the actions an agency has established to ensure data quality, whether the data is collected in-house or by a contractor. Common quality assurance techniques include documented policies and procedures to establish data quality tolerance limits, independent reviews of collected data, and training of data collection crews. Data management strategies are discussed in more detail in Chapter 7.

To evaluate the accuracy of models and assumptions, agencies can include multiple scenarios in their life cycle planning analysis to test the impact of different decisions. This type of sensitivity analysis can be helpful in identifying areas in need of further research or developing contingency plans if the initial assumptions turn out to be inaccurate.

To understand whether time and effort should be invested in minimizing uncertainty, a risk-based approach can be used. Assuming the consequence arising from a defined issue or event remains the same, the cost in terms of data collection of reducing uncertainty can be investigated. As an example, the condition state of an asset, as determined using a visual approach, may not provide the required level of insight, which results in poor or unknowable treatment decisions. To minimize the uncertainty, extra testing can be carried out. The level of testing would be defined by the risk-cost reduction ratio. Similarly, with climate change, how much would have to be invested in studies to understand the effects on asset longevity? Thus, through risk management, an agency determines which risks are tolerable and which must be actively managed through investigations, studies other research. The risks are identified, prioritized, and tracked using a risk register (see Chapter 2). For those risks that should be managed, plans are developed to outline actions that will be taken to mitigate threats or take advantage of opportunities, as discussed in Chapter 6.

How-to

Life Cycle Planning for Pavements

A highway network consists of pavements at different phases of serviceability, and addressing the network's needs requires both current pavement condition data to identify the amount and severity of deterioration present, as well as the ability to forecast how those conditions will change over time. LCP is based on a network-level analysis that considers both economic and engineering factors to determine the most cost-effective strategies to achieve desired pavement conditions. This How-to guide provides an overview of a process agencies can follow to carry out an LCP analysis for its pavement assets.

1. Define Subsets of Network for Analysis

Define the various subsets of the pavement network that you will be analyzing. For example, an agency might analyze Interstates separately from the rest of the National Highway System (NHS), especially if the typical treatment strategies differ.

2. Establish Treatment Rules and Costs

Establish treatment rules and costs for a variety of treatment options that cover pavement needs over the life of the asset. In addition to setting up treatment rules for the types of treatments the agency normally uses, it may be useful to establish a set of rules that favor an aggressive series of preservation treatments to determine whether that strategy would result in better conditions at a lower cost.

3. Input Analysis Parameters

Input the analysis parameters, including the length of the analysis period, the treatment rules, and the estimated funding to be used, into the pavement management system. The analysis period should be at least 10 years, but may be longer to evaluate long-term impacts.

4. Run Analysis and Evaluate Effectiveness

Run the analysis and evaluate the effectiveness of the various treatment strategies established during step 2. The analysis is likely to show that strategies that include preventive maintenance treatments that keep pavements in good condition will result in better long-term conditions than strategies that include only rehabilitation or reconstruction activities when the same budget is applied to each strategy. Alternatively, the pavement management analysis could be used to show that a preservation strategy can achieve the same network conditions as a more traditional rehabilitation strategy for a lower cost.

5. Summarize Results

Summarize the results of the analysis and provide the recommended strategy for each network subset for use in developing the financial plan and investment strategies for your TAMP.

LCP for Pavements

1 Define subsets of network for analysis

2 Establish treatment rules and costs

3 Input analysis parameters

4 Run analysis and evaluate effectiveness

5 Summarize results

Applying Other Life Cycle Management Approaches

Assets that are managed using an interval-based or reactive management strategy require different approaches for planning and optimizing work than assets managed using condition. The life-cycle plans for these assets range in terms of sophistication depending on the available data.

When to Use Approaches Other than Condition-Based Management

Condition-based management requires a commitment to reliable asset condition information. The necessary level of effort is not likely to be appropriate for some assets. Some assets do not lend themselves to management using a traditional condition-based management approach. The four most common reasons assets do not fit a condition-based approach are as follows:

- The assets do not have a typical life cycle – This group of asset classes includes rock slopes or other perpetual features that do not have predictable deterioration patterns.
- The assessment of condition or performance may not be feasible – The most common type of assets in this second group are geotechnical or utility assets for which many elements may be buried or otherwise inaccessible. The absence of a rating methodology may also drive the management of assets using something other than a condition-based approach.
- The life cycle is driven by factors other than condition – There are many assets that are replaced when they are worn out or obsolete. Technology assets, which are susceptible to obsolescence at a frequency similar to their functional service lives, are examples of assets that fall into this category.
- The assets have long service lives and the failure of individual assets presents limited risks to safety or system performance – Examples of these asset classes include guardrail, gravity retaining walls, or highway lighting.
- The performance expectations require the asset to remain in near-new condition. For safety-critical assets, replacement may be necessary before signs of deterioration are evident. This is most common in risk-averse industries such as aviation. However, contractual arrangements, such as in public-private partnerships (P3), may require condition or performance targets that warrant a life cycle management approach other than condition-based.

As discussed earlier, assets that fall in these categories are typically managed using an interval-based approach or a reactive approach. Some agencies also use a risk-based approach for certain types of assets, such as rockfall management. These three different approaches are briefly explained, and examples are provided for each approach.

Alternative Life Cycle Management Approaches

Three alternative life cycle management approaches are discussed in this section. These are interval- or age-based strategies, reactive strategies, and risk-based strategies.

Interval- or Age-Based Management

Interval- or age-based strategies can be utilized for failure-critical assets, assets subject to obsolescence or assets with no or limited maintenance actions. Age-based strategies replace assets after a given time in service without regard to the asset's condition at that time. This approach can also be used for very short-lived assets, such as paint markings. Advantages include proactive minimization of failure and reduction of uncertainty in funding needs. An agency that replaces signs on a 7-year cycle or replaces pavement lane markings annually is using an interval- or age-based approach to manage its assets.

Interval-based strategies are also useful for assets that do not show physical wear, but are safety- or operations-critical.

Reactive Management

Reactive strategies can be used for assets that have long service lives and limited maintenance options. Reactive strategies can be based on the results of an on-going monitoring program or on event reporting. Examples of assets that may be monitored periodically to check that they are working as intended includes retaining walls and overhead sign structures. Assets that may be more likely to be maintained based on a report that the asset is damaged or no longer working include light bulbs and guardrail.

Practice Example
Interval-Based Approach to Managing ITS Assets

Nevada DOT

Nevada DOT recognized that the level of investment in ITS equipment (e.g., closed-circuit cameras, dynamic message signs, flow detectors, highway advisory radios, environmental sensor stations, and ramp meters) was increasing significantly and the importance of this equipment to network operations was growing. As a result, the DOT chose to establish a method of managing its ITS assets that would minimize the risk of failure and provide information to support budgeting activities. However, since the DOT had limited data on its ITS components, a process was developed that relied on the following factors to establish maintenance cycles:

- Historical performance
- Manufacturer recommended service life
- To determine the condition of ITS traffic cameras, Nevada DOT developed a transition probability matrix with four condition criteria based on the device manufacturers' recommended service life as follows:
  - **Good –** device age is less than 80 percent of the manufacturer's recommended service life
  - **Low risk –** device age is between 80 to 100 percent of the manufacturer's recommended service life
  - **Medium risk –** device age is between 100 to 125 percent of the manufacturer's recommended service life
  - **High risk –** device age is greater than 125 percent of the manufacturer's recommended service life

The transition probability matrix was used to model ITS asset deterioration and program maintenance actions over a 10-year analysis period via the use of a simple spreadsheet tool. The results of this analysis showed an interval-based approach to managing ITS assets would result in an estimated savings of $1.1 million over a 20-year period.

Source: Nevada DOT TAMP (2018)

Risk-Based Management

While all management strategies are risk-based, there are times when risk assessments are used directly as the measure to establish objectives, set targets, drive decision making, or assess progress. This approach is used when the condition of the asset does not directly represent the level of asset performance, and the potential impact of an asset's condition on system performance must be considered. This approach is commonly used for managing slopes and other geotechnical assets.

Practice Example
Risk-Based Geohazard Management Program

Colorado DOT

Colorado DOT responds to between 50 and 70 geotechnical emergencies a year. The traditional approach to managing rockfalls was based on the size and frequency of rockfalls. This approach did not consider the criticality of the facilities that could be impacted by a geohazard event. Since 2013, the Colorado DOT has used a risk-based approach to evaluate and prioritize geohazard mitigation activities based on the size of the geohazard areas and the frequency of falls. Colorado DOT's approach includes a measure of Risk Exposure (RE), which is based on three components:

- Average Annual Daily Traffic (AADT).
- Likelihood of a Vehicle Being Affected by a Geohazard Event. This metric considers site-distance, the number of previous rock-fall accidents, and a measure of how frequently a vehicle is below the hazard on a daily basis.
- Reduction Factor. This considers the effectiveness of prior mitigation actions, to reduce the RE score.

Colorado DOT's geohazards program uses the RE to allocate an annual budget of about $10 million to manage geohazards. Due to the inherent uncertainty of geohazard management, in addition to the geohazard management program, maintenance staff regularly patrol highways known to have geohazards. If a hazard requiring immediate action is identified, maintenance crews respond promptly. Using the RE for prioritization allows Colorado DOT to focus its efforts on reducing the impact of geohazards on users of the highway system.

Implementing Life Cycle Management

Implementation of life cycle management often requires agencies to review existing data sets, processes, and policies to ensure that the recommended scenarios are reflected in the projects and treatments that are programmed and constructed. Within transportation agencies, this often requires improved coordination between business units such as planning, programming, engineering, maintenance and operations. Information about strengthening organizational communication and coordination was discussed in Chapter 3.

This section focuses on the aspects of implementation that are most directly related to using life cycle management results to maximize the service lives of infrastructure assets as cost-effectively as possible. It highlights the need to evaluate agency policy, data issues, and work processes to support life cycle management.

Linking Life Cycle Strategies to Asset Management Policy

Agency policies influence the types of decisions that are made within an agency and the priority with which activities are funded. The life cycle management approach selected for each asset class will impact the type of policies, procedures, and data required to support investment decisions to ensure alignment between planned and actual work activities.

Aligning the organization to support the implementation of life cycle management strategies involves many of the same types of organizational change processes discussed in Chapter 2. As part of this alignment, an agency must ensure that it has in place the processes and resources needed to deliver the work activities required for executing the selected life cycle strategies.

Chapter 2 introduced the importance of establishing Asset Management policies to help integrate asset management at all level of an organization. An Asset Management policy can support life cycle management by establishing processes for setting realistic performance objectives and treatment strategies that focus on a commitment to sound, long-term investments. The following examples demonstrate how agencies can select a life cycle approach that supports the agency's higher-level policies.

Data Required for Implementation

All life cycle management approaches need inventory and performance information, but the extent, detail, accuracy, and precision of the required information varies greatly given the chosen approach.

Assets that are managed using a condition-based approach rely on detailed inventory and performance information so that current and future conditions can be estimated, and the benefits and costs associated with each viable strategy can be evaluated. Interval-, time-based, and reactive approaches can be performed with less detailed information about the assets. Agencies using these approaches may estimate the size and age of the inventory at early levels of maturity. Over time, the type of information available and the level of detail associated with it may improve, allowing the agency to mature in terms of its analysis capabilities.

Table 4.3 provides examples of typical management strategies for common highway asset classes and the types of information used to support each one. The information in table 4.3 reflects general trends in transportation agencies. In practice, each agency must identify the specific elements and data requirements needed to support their needs within resource constraints. Chapter 7 addresses methods of collecting information efficiently (see table 7-3) and Chapter 6 stresses the importance of keeping inventory and performance data current. Establishing data governance structures to manage asset data is also an important consideration, as discussed in Chapter 7.

Examples

Linking Maintenance Strategies and TAM Policies

The following hypothetical examples show how policy and management strategy work together to deliver transportation services and manage risks.

Reactive Strategy Example – *Agency A* has determined its guardrail inventory is generally in good condition and typically replaced as part of pavement rehabilitation projects. On average, replacements occur at least every 30 years, which is more frequent than the expected service life ranging from 40 years for cable to 75 years for concrete barrier. As a result, the agency can accept a life cycle strategy of maintaining a complete inventory and annual inspection of a random two-percent sample.

This life cycle strategy introduces the risk of a rail being damaged by collisions or other events and left in service, presenting a danger to highway users. To manage this risk, the agency implements a policy of repairing all damaged guardrail within 3 weeks of becoming aware of damage. Additionally, internal procedures are put in place to notify area maintenance managers of incidents reported through the state police accident reporting system, and standby maintenance contracts are established for guardrail repair to ensure adequate resources are available in compliance with the new policy.

Condition-Based Maintenance Example – Agency B has determined it can provide significant, long-term performance improvement in average bridge condition and service life if it can increase its investments in bridge maintenance activities like sealing concrete, repairing joints and spot painting steel. To fund this initiative, however, the agency must replace three fewer bridges on average each year. The short-term impact of this new life cycle strategy is an increase in the risk of unsafe conditions occurring on bridges that would have been replaced under the previous strategy. To overcome this risk, the agency increases the frequency of inspections on bridges exceeding the level of acceptable risk according to analysis from its bridge management system, and a series of standby contracts are established to provide rapid response of specific structural repairs to extend the service lives of poor bridges by addressing only critical structural deficiencies or risks.

Incorporating Life Cycle Management into Work Planning and Delivery

Life cycle management approaches and corresponding life cycle strategies are the means by which agencies identify the work necessary to meet their asset management goals within funding constraints. However, for those asset management goals to be met, the necessary work must actually be delivered. This requires the recommendations from life cycle analyses to be incorporated into the business processes by which the agency identifies, prioritizes, programs, designs, and delivers work. In most agencies this includes multiple business processes and funding streams. The following subsections describe how life cycle management can be incorporated into common processes within transportation agencies.

Planning and Programming

The planning process seeks to identify the set of investments that will effectively and efficiently achieve an agency's goals and objectives. As an agency alters its approach to managing assets, this may change assumptions previously influencing the planning process. Significant changes in an agency's approach to managing its assets can require updates to long-range or strategic plans. Similarly, changes in long-term objectives or plans can prompt a change in life cycle strategy or approach.

Coordination is needed between long range transportation planning, performance-based plans such as the TAMP, and programs of work, such as TIPS and STIPs (see chapter

2). In particular there is a need for alignment between the financial planning procedures and documentation between these different efforts and products. Although programs tend to be relatively short term, often 1 to 4 years in length, agencies must identify investment needs several years in advance to ensure projects can be delivered when required. Complex reconstruction or modernization projects can take 10 years or more to deliver from scoping to construction. Thus, it is important to keep planners informed of changes in selected life cycle strategies. Changing new life cycle strategies may lead to significant differences in the projects selected.

Table 4.3 Typical Maintenance Strategies and Supporting Data

Asset Type	Typical Maintenance Strategy	Typical Information Collected and Used
Pavements	Predictive, condition-based maintenance	• Linear referencing system • Segmentation with unique IDs • Inventory (e.g., width, pavement type, and other identifying attributes) • Condition data (e.g., ride quality cracking, rutting, faulting, and others) • Deterioration models • Available treatments • Treatment unit costs
Bridges	Predictive, condition-based maintenance	• National Bridge Inventory Data (NBI) • National Bridge Element Condition (NBE) Data • Vulnerabilities (e.g., scour, seismic, flood) • Deterioration Curves • Treatment options • Unit costs
Overhead Sign Structures	Monitoring-based or Interval-based maintenance	• Inventory Data, modeled after NBI • Element level condition data, modeled after NBE • Design life • Structural specification (e.g., proper bolt torque)
ITS Assets	Interval-based maintenance	• Location • Asset ID • Inventory data to identify type or class • Install date • Manufacturer recommended service life
Guardrails	Reactive maintenance	• Location • Type • Functional requirements

Source: FHWA. Handbook for Including Ancillary Assets in Transportation Asset Management Programs. 2019. Prioritizing Assets for Inclusion in Transportation Asset Management (TAM) Programs.

Project Engineering

Life cycle management is a framework for identifying the appropriate treatments throughout an asset's service life to maximize performance. Project engineering includes the processes for packaging work into contracts for delivery. Thus, project engineering is responsible for ensuring the right treatment is delivered at the right time and within the anticipated cost. Additional details on work packaging to support asset management are provided in chapter 5.

Maintaining strong internal controls ties project decisions to their impacts on anticipated asset performance. Project schedule changes may cause inappropriate treatments to be applied to assets, resulting in unnecessarily high costs or poor performance. Scope changes often lead to cost changes, and while cost changes may be addressed for a specific project, the funds added to that project would not be available to address other system needs.

Use of Agency Maintenance Forces

Effective delivery requires adequate labor capacity with appropriate training, proper equipment, and necessary materials. Changes in an agency's management approach can alter the requirements for any of these aspects of maintenance management. The necessary treatments cannot be delivered if a properly sized and equipped crew cannot be assembled. Maintenance staff cannot administer treatments for which they are not properly trained or correctly supplied. Therefore, it may be important to have maintenance management staff actively engaged in the process of identifying preferred life cycle management approaches.

Practice Example

Life Cycle Management Across a Diverse Portfolio

The City of Fredericton, New Brunswick

The City of Fredericton has, over the last 15 years, implemented several life cycle management strategies that have significantly changed how it delivers municipal services with its infrastructure. Three examples are briefly summarized below:

- Long term life cycle planning: Infrastructure accounting policy changes led to the City establishing long term replacement forecasts for each asset class to estimate the sustainable level of funding required for investment for capital budgeting. This required a complete inventory of their assets, changes in how future replacement costs were estimated, as well as changes to the analysis period used for long term planning. At least one life cycle for all assets had to be captured in the forecast horizon.
- The City implemented a Lean Six Sigma strategy to assess and improve processes and service delivery. This methodology helped identify efficiency opportunities, but also identified intervention strategies that were not previously considered in project scoping.
- The City reviewed service requirements in terms of labor and equipment required as part of the lean approach, and in some circumstances managed to create time savings or hard dollar savings or both, hence shifted resources to have different roles for service delivery. In some cases, the service delivery was contracted to external service providers.

How-to

Determining What Data Is Needed to Support Life Cycle Management

Once a maintenance strategy for an asset class or subclass (e.g. condition-based, interval-based or reactive) is selected, data is required to support the types of decisions needed to manage the asset. The type of data collected will vary based on the selected strategy and the specific decisions needed to be made to manage the asset class. The objective is to make informed, data-driven decisions on the appropriateness, timing and priority of treatment options over the service lives of specific assets. These decisions are supported by field collection of inventory and condition data, as well as the development of higher-level measures and analysis results from that data. The following sections describe methods for determining what data is essential or desirable to support maintenance decisions and the delivery of work.

Regardless of the life cycle approach selected (e.g. condition-based, interval-based or reactive), data is required to support the types of decisions needed to manage the asset. The type of data collected will vary based on the selected approach and the asset class or sub group. As described in this chapter, data is needed to support decision making about the type and timing of actions that can be taken to delay or address asset deterioration, damage, premature failure, or other performance decline. In some cases, the data can directly trigger decisions, such as accident data informing a process to repair or replace guard rail. In other cases, the data is used to support analyses that inform decision making processes, such as condition-based management.

While supporting investment decisions may be the primary purpose for collecting and managing asset data, agencies may have other purposes, such as internal or external reporting, or mandates. Agencies need to make hard choices about what data is essential to support business practices, and what data is merely desirable. Once that is determined the agency must next evaluate the benefit derived from the desirable data along with the cost and benefit of collecting and managing that data. This how-to guide provides a simple 3-step approach to identifying and evaluating essential and desirable asset data, to determine which data should be collected to support life cycle management. This approach is based on material from the FHWA document, *Handbook for Including Ancillary Asses in Transportation Asset Management Programs*, which is pending publication in 2019. The Handbook provides additional detail and several examples of data elements typically collected to support life cycle management of different assets. Additional details on data collection and management can also be found in chapter 7 of this guide.

What Data is Needed

1 Determine the Essential Data to Support the Maintenance Strategy

2 Determine Desired Data to Support the Maintenance Strategy

3 Align Business Processes

1. Determine the Essential Data to Support the Maintenance Strategy

While the management approaches discussed in this chapter vary in their degree of complexity, all three require some essential data, which can be categorized into asset class and subclass information, unique identifier information, individual asset location information and action trigger(s). The following sections describe how to determine the best means of addressing each of these data elements.

How-to

Determining What Data Is Needed to Support Life Cycle Management

Asset Class and Subclass

Asset class and subclass are defined by specific attributes that can group individual assets into sets with common management options. Asset classes and subclasses should only be defined to the level of detail that supports treatment selection, prioritization, or delivery. For example, within the asset class ‘guardrail’, it may be advantageous to identify subclasses of ‘box beam’, ‘W beam’ and ‘PCC barrier’. However, there is likely no benefit to further dividing box beam guiderails into subclasses based on the post type or spacing.

Unique Identifier

For each asset managed using a condition-based approach, a unique identifier is required to link inventory and condition information to the specific asset in the field so it can be evaluated for work as an independent unit. This can become difficult for assets that are components of a system, such as closed drainage systems or roadside sign arrays. In these cases, there may be a need for a parent-child relationship between different asset classes. In the case of sign arrays, the support structure and each sign panel attached to it may be considered individual assets. It is good practice to have a universal system for developing unique identifiers that avoids duplicate identifiers between asset classes.

Individual Asset Location

There are many ways of determining and documenting asset location, including coordinates, linear referencing, street addresses, stationing from physical benchmarks and others. Ideally, an agency has one common referencing approach to use for all assets.

What Data is Needed

1. Determine the Essential Data to Support the Maintenance Strategy
2. Determine Desired Data to Support the Maintenance Strategy
3. Align Business Processes

Action Trigger

The selected RCM strategy will determine the type of data needed to support action triggers:

- Condition-based strategies require some measure of condition relating to both the performance of the asset and the applicability of potential treatment options. For some assets, such as culverts or drainage structures, this will require multiple data elements to describe aspects of the different means of deterioration or failure, for example sediment or structural deterioration. For other assets, such as sign panels, there may only be one measure of condition, such as retroreflectivity.
- Interval-based strategies require an age element. This could be stored as an installation date or date since last treatment. In the case of the latter, additional data elements to may be needed to describe the treatment. If this information is not known, estimates can be used at early levels of maturity. For example, if signs are generally replaced every 10 years, an agency may assume 10 percent of the inventory needs to be replaced each year.
- Reactive strategies require a means of identifying if and when an event has occurred that requires a response. Examples include identification by field staff or information from accident reports identifying damage or failure.

2. Determine Desired Data to Support the Maintenance Strategy

Data collection, storage and maintenance is expensive. It is important each data element collected has a clear purpose and use in development or delivery of work plans and projects. The following is a partial list of purposes for collecting data:

- Provide additional clarity, accuracy or precision to the essential data collected
- Support different work units within an agency, such as engineering, operations or planning

How-to

Determining What Data Is Needed to Support Life Cycle Management

- Assist in generating maintenance work orders
- Provide additional detail to manage risks
- Provide details on maintenance intervals
- Support project development through integration with other asset data sets

3. Align Business Processes

Supporting life cycle management requires the collection and management of data to support multiple business processes, including planning, design, construction, maintenance and operations. Each of these processes has data requirements and may have already been collecting some data on the asset to support those processes. It may be necessary to change business processes to use data already being collected or can be collected more efficiently. This process is described in more detail in Chapter 7.

What Data is Needed

1 Determine the Essential Data to Support the Maintenance Strategy

2 Determine Desired Data to Support the Maintenance Strategy

3 Align Business Processes

Checklist

Considerations to Support the Successful Implementation of a Life Cycle Approach to Managing Assets

The following checklist is provided to support efforts of implementing life cycle management of transportation assets. It can be used to help an agency assess whether future changes to policies, data, or business processes could advance the maturity of its life cycle management practices. This checklist should be completed for each asset within, or under consideration for inclusion in an agency's asset management program.

Levels of Service

- ☐ **Have stakeholders been identified for establishing customer-based levels of service?**
- ☐ **Has a communications process been established to understand stakeholder wants?**
- ☐ **Have KPIs been developed to address stakeholder wants?**
- ☐ **Have performance-based levels of service been established for each KPI?**
- ☐ **Have maintenance levels of service been established for the asset class to support achievement of the KPIs?**

Life Cycle Strategy Development

- ☐ **Has a clear life cycle approach been selected?**
- ☐ **Have performance or condition thresholds been established to define failure?**
- ☐ **Have performance models been developed or adopted?**
- ☐ **Have treatments been defined?**
- ☐ **Have unit costs been established?**
- ☐ **Has a life cycle plan or strategy been developed for the asset?**

Checklist

Considerations to Support the Successful Implementation of a Life Cycle Approach to Managing Assets

Business Process Implementation

- ☐ Is there a centralized individual or group who coordinates the integration and use of life cycle planning across business areas?
- ☐ Have cross-functional teams been established to communicate between asset managers and other organizational units?
- ☐ Does the agency's asset management policy provide the needed support for life cycle management of the asset?
- ☐ Is the life cycle strategy included in the development of relevant strategic plans?
- ☐ Is the life cycle strategy considered during funding allocation processes?
- ☐ Is the life cycle strategy considered during capital project prioritization, selection, or programming?
- ☐ Is the life cycle strategy considered by project development staff when making decisions on project scoping?
- ☐ Does the agency regularly review the match between planned and actual investments based on the life cycle strategy?

Data and Systems to Support Life Cycle Management

- ☐ Do staff have the data needed to establish desired levels of service or KPIs?
- ☐ Do staff have the data needed to track performance according to KPIs?
- ☐ Do staff have the data they need to develop life cycle strategies?
- ☐ Do staff have the management systems they need to develop life cycle strategies?
- ☐ Are the prediction models, treatment rules, and impact rules representative of what is included in the life cycle strategies?
- ☐ Do asset managers routinely update treatment definitions and unit costs?
- ☐ Do asset managers routinely update performance models?
- ☐ Do asset managers routinely update decision trees, or prioritization criteria?
- ☐ Are life-cycle analysis results used by planning staff during the development of strategic plans?
- ☐ Are life cycle analysis results used to support programming, or project prioritization practices?
- ☐ Are life cycle analysis results used to inform the maintenance work planning (work order) process?
- ☐ Is life cycle planning data and analysis results provided to external stakeholders?

Maturity Scale

This table provides an example maturity scale for some of the key TAM practices described in this chapter.

Aspect of Practice	Level of Maturity	Typical Agency Status
Levels of Service	**Emerging**	• Customers are identified, but outreach is not formalized. • Some technical levels of service or KPIs are defined and considered when intervention alternatives are being evaluated.
	Strengthening	• Customer groups are defined and some communication practices are in place to assess wants. • KPIs are established, but may not be tightly tied to business decisions. • Maintenance levels of service are established, but there is not a tight connection to KPIs. • Technical levels of service are defined, and measured to evaluate the effectiveness of past investment and operational decisions.
	Advanced	• Customer groups are defined and clear policies and procedures are in place to assess wants. • Customer-based KPIs and maintenance levels of service are established at the strategic, tactical, and operational levels. • Agency performance is routinely measured and reported to all internal and external stakeholders.
Managing assets for their life cycles	**Emerging**	• Alternative management strategies are considered for high value / critical asset classes in the portfolio and selected based on efficiency and effectiveness of the transportation network. • Asset reliability is qualitatively considered in a systematic way for some asset classes. • Reactive and interval-based approaches that are based on risk assessments are used where appropriate. • Management strategies are periodically re-evaluated to determine if a change in management practice would be more effective. • Deployment of maintenance crews, capital projects, and network operation resources are coordinated to ensure the right interventions are occurring in the right locations, at the right time on the transportation network to deliver mobility service levels at an acceptable cost and level of risk.
	Strengthening	• Appropriate condition, interval and reactive based management strategies have been established for most asset classes. • Asset reliability is well understood and is aligned with risk tolerance in the agency. • Assets are planned, acquired and managed with an awareness of the costs, risks, and service performance characteristics over the entire life cycle. • Appropriate management strategies are established and periodically re-evaluated to determine if a change in management practice would be more effective. • Deployment of maintenance crews, capital projects, and network operation resources are coordinated to ensure the right interventions are occurring in the right locations, at the right time on the transportation network to deliver mobility service levels at an acceptable cost and level of risk.
	Advanced	• Appropriate condition, interval and reactive based management strategies have been established for every asset class in the portfolio, to support management of the transportation network efficiently and effectively. • Asset reliability is well understood and is aligned with service expectations and risk tolerance in the agency. • Strategic, tactical and operational activities directly consider alternatives that balance service delivery and investment of resources. • Reactive and interval-based approaches that are based on risk assessments are used where appropriate. • Management strategies are periodically re-evaluated to determine if a change in management practice would be more effective. • Deployment of maintenance crews, capital projects, and network operation resources are coordinated to ensure the right interventions are occurring in the right locations, at the right time on the transportation network to deliver mobility service levels at an acceptable cost and level of risk.

Maturity Scale

Aspect of Practice	Level of Maturity	Typical Agency Status
Data and Systems for Life Cycle Management	**Emerging**	• A computerized maintenance management system is being implemented / customized to better understand operations and maintenance activities within the agency. • Some basic asset modeling is used to predict asset performance in the future for financial planning purposes. • Computer management systems meeting the minimum federal requirements are implemented and used for compliance.
	Strengthening	• A computerized maintenance management system captures operations and maintenance costs within the agency and assigns these to asset appropriately. • Appropriate probabilistic and deterministic modeling techniques are used to predict asset performance for high value assets.
	Advanced	• A computerized maintenance management system captures operations and maintenance costs within the agency, and supports trade-off analysis between capital investment and operations and maintenance intervention alternative tactics • Appropriate probabilistic and deterministic modeling techniques are used to predict asset performance in the future, and inform financial planning and intervention selection.

References

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For additional references on methods used to evaluate the condition of assets using a condition-based approach, additional resources are available through the Maintenance Quality Assurance (MQA) websites for various state DOTs. In recent years, AASHTO has been working with state DOTs to compile MQA resources on the following SharePoint site.
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Selecting a Life Cycle Management Approach and Reliability Centered Maintenance

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Asset-Specific Life Cycle Management

For additional references on methods used to evaluate the condition of assets using a condition-based approach, additional resources are available through the Maintenance Quality Assurance (MQA) websites for various state DOTs. In recent years, AASHTO has been working with state DOTs to compile MQA resources on the following SharePoint site.

Using a Life Cycle Planning Process to Support Asset Management. FHWA. The document describes a best-practice approach to implementing life cycle management, in a way that satisfies the federal requirements for life cycle planning in State DOT risk-based TAMPs (23 CFR 515).
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