Identification of Effective Next Generation Pavement Performance Measures and Asset Management Methodologies to Support MAP-21 Performance Management Requirements

Volume 2: Methodologies to Enable Full Implementation of a Comprehensive Asset Management Plan

Final Report

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16. Abstract

Quantifying transportation system performance is a matter of developing a clear description of what customers and stakeholders want and value. These strategic values are stated in guiding documents such as MAP-21, the Moving Ahead for Progress in the 21st Century Act (P.L. 112-141), which was signed into law on July 6, 2012. Under MAP-21, highway agencies are required to develop an asset management plan that includes analyses of gaps in performance, life-cycle cost analysis for optimal life-cycle management, risk analysis, financial plan for a minimum of 10 years as well as investment strategies to achieve a desired state of good repair of assets. One of the two objectives of this study is to identify or conceptually develop methodologies to enable full implementation of a comprehensive asset management plan, including trade-off analysis from a common ground among disparate assets that are traditionally individually assessed and managed. This study proposes a methodology to enable full implementation of a comprehensive TAM Plan as laid out by MAP-21. The proposed framework starts with the basic objectives and management concerns common to practically all highway agencies, using these as the foundation for a common set of cross-asset methodologies to support decision making in all of the fundamental business processes necessary to implement Transportation Asset Management (TAM) Plans. This study presents a process on how to apply the proposed TAM methodology at both the project and network level for trade-off analyses and decision making.

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SI* (MODERN METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
		Length		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		Area		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		Volume		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		Mass		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		Temperature (exact degrees)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

Approximate Conversions from SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
		Length		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		Area		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		Volume		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		Mass		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		Temperature (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F

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LIST OF ABBREVIATIONS

DOT	Department of Transportation
EUAC	Equivalent Uniform Annual Cost
FHWA	Federal Highway Administration
KPI	Key Performance Indicator
LOS	Level of Service
MAP-21	Moving Ahead for Progress in the 21st Century Act
MP&R	Maintenance, Preservation and Rehabilitation
NPRM	Notice of Proposed Rulemaking
NPV	Net Present Value
RSI	Remaining Service Interval
RSL	Remaining Service Life
SGR	State of Good Repair
STIP	Statewide Transportation Improvement Program
TAM	Transportation Asset Management
TERM	Transit Economic Requirements
TIP	Transportation Improvement Program

EXECUTIVE SUMMARY

The objective of this study is to identify or conceptually develop methodologies to enable full implementation of a comprehensive asset management plan, including trade-off analysis from a common ground among disparate assets that are traditionally individually assessed and managed.

State and federal enabling legislation, mission statements, strategic plans, and industry standards define a typical and common set of performance objectives and business processes which, together, establish commonality among asset classes. These statements of policy provide the justification for constructing and preserving the elements of the transportation system, and also set the framework for evaluating service quality and effectiveness. In most cases these objectives are measurable, and are being measured.

The proposed framework starts with the basic objectives and management concerns common to practically all highway agencies, using these as the foundation for a common set of cross-asset methodologies to support decision making in all of the fundamental business processes necessary to implement Transportation Asset Management (TAM) Plans (Figure 1). The framework is developed from two perspectives:

Strategic:

- Statements of performance objectives, such as those listed in 23 USC 150(b) and further developed in the proposed 23 CFR 490, define the scope of a fully-implemented asset management process. These include goal areas such as condition safety, mobility, and environmental sustainability.
- Statewide and metropolitan service plans establish development patterns, corridor emphases, and service priorities covering the same time frame as TAM Plans.
- Essential ingredients of a Transportation Asset Management Plan as described in 23 USC 119 and in the AASHTO Guides for Transportation Asset Management, describe strategic management concerns common to all asset classes, including long term cost minimization, risk management, and fiscally-constrained investment planning.

Tactical:

- Transportation agencies have a wide variety of existing data collection capabilities to monitor the condition and performance of their assets and of the collective network. Some of these, such as National Bridge Inventory data, are highly standardized; others are moderately standardized by industry manuals and conventions. For assets other than pavements and bridges, emerging standards can be identified.
- Thinking in terms of the next 20-50 years, technological innovation in data collection will very likely improve the range of typical agency data collection capabilities, improving agency knowledge of asset and network performance.
- Agencies vary in the level of centralization or decentralization of asset management decision making. Most agencies, however, assign some aspects of asset-level planning

discretion at a highly localized level where decision makers highly familiar with individual assets make tactical decisions about project scope and timing. Similarly, most agencies centralize some aspect of policy and resource allocation decision making at the statewide level. In most cases there are also intermediate levels of decision making.

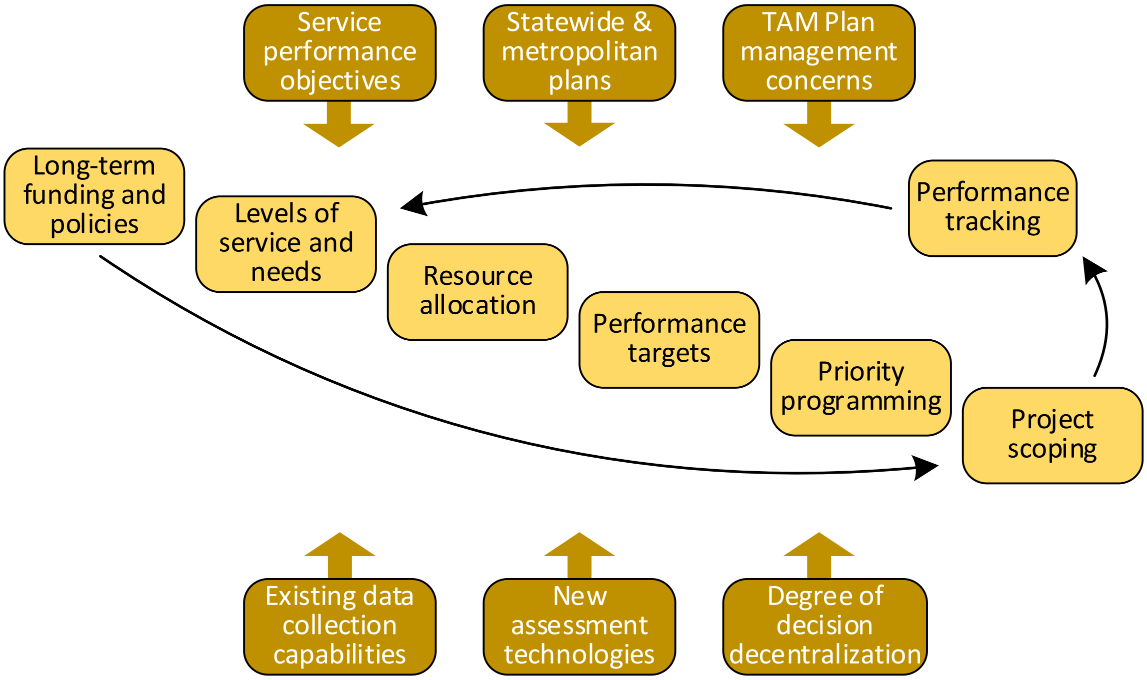

Figure 1. Major framework elements.

The strategic and tactical perspectives have to be reconciled in order to establish a fully implementable framework. How this is done can vary from one agency to another, but typically incorporates a set of business processes such as:

- Negotiation of long-term funding mechanisms, and development of strategic direction, policies, and standard operating procedures;
- Development of level of service standards and corresponding needs;
- Allocation of anticipated resources, including funding and staffing;
- Establishment of performance targets, constrained by fiscal scenarios;
- Priority programming and the STIP process;
- Conceptual planning of projects; and
- Reporting and tracking of network performance, which provides metrics and expectations to drive future cycles of these processes.

It can be observed that only raw condition data collection and some aspects of project planning are necessarily and consistently specific to asset classes; the strategic constraints and business processes are often or completely asset-generic. Performance tracking and target-setting are asset-specific under the proposed federal rules for condition, but can be generic in state practice (e.g. condition indexes) and for performance concerns other than condition (e.g. safety, mobility). Priority programming using benefit/cost analysis can be generic, even though many agencies retain the legacy practice of programming within asset class silos. The selection of appropriate treatments is often asset-specific, but agencies often create corridor-level projects that include all of the asset classes along a corridor, which may be prioritized together. Working from this perspective provides ample potential to find common ground for performance assessment and tradeoff analysis across asset classes.

The methodologies supporting TAM decision-making rely on a typical set of tools, which include:

- Agency-adopted policy and procedure documents and standard operating procedures;
- Management systems for pavements, bridges, and other asset classes;
- Geographic information systems and other agency systems which may be data sources (e.g. traffic and accident data), presentation media (e.g. maps and charts), and/or analysis tools (e.g. traffic flow simulation, frequencies of natural hazards);
- Specialized information technology tools to support individual business processes on either a systematic or ad hoc basis (e.g. spreadsheets, HERS-ST).
- Agency research products such as models of deterioration, costs, and risk;
- Agency standards for levels of service and design criteria;
- Management judgments and prerogatives;
- Industry standards, such as inspection and maintenance manuals, design specifications, and AASHTO guidelines; and
- Industry research products, particularly those of the National Cooperative Highway Research Program and FHWA-funded projects.

All of these ingredients are developed by a variety of actors, each with a constrained set of responsibilities within the broader asset management process. They constitute an ecosystem. The present document describes the constraints under which this ecosystem must flourish, and a range of methodologies that can serve in the middle tier to reconcile the strategic and tactical perspectives to fully implement a comprehensive TAM Plan.

Although the Task description singles out NCHRP Project 08-91 (Report 806) as a starting point, that project focuses on just one set of tools, which rely heavily on judgment as data. A broader perspective will help to identify the roles that the 08-91 products might play, alternative approaches to serve the same roles, and criteria to support the selection of an appropriate methodology for a given agency. Some refinement in the Report 806 framework, and more appropriate technology choices, will lead to substantial improvements including:

- A better fit of tradeoff analysis methods to the actual decision making contexts that agencies face, including the existence of multiple decision makers.

- More appropriate definition of the scoping and timing alternatives that need to be produced by management systems in order to satisfy the full set of decision support requirements.
- A more comprehensive performance management framework that more naturally accommodates assets other than pavements and bridges.
- Improved guidance that feeds back from cross-asset decision making to the individual asset-specific preservation programming and delivery processes.

It is especially important to ensure that near-term and long-term costs are fully and appropriately considered; that risk management is explicitly supported; that existing and potential industry standards and data are exploited; that the process be objective, transparent, robust, repeatable, consistent, and accountable; and that the methodology support validation and continuous improvement.

CHAPTER 1. INTRODUCTION

Transportation Asset Management as a focus of professional practice has existed for pavements and bridges since at least the 1960s, although the recognition of the need for systematic preservation can be dated to 1775 (Haas et al 1994). Efforts to integrate pavement and bridge management, and to extend the discipline to other asset classes, began with database and geographic information system projects in the 1980s, and extended to priority-setting and resource allocation activities in the 1990s (FHWA 1998).

Since that time, recognition of the need for cross-asset decision support has broadened, yet data collection processes and quantitative analysis have continued to be highly compartmentalized by asset class (Cambridge Systematics, Inc. 2002). This has contributed to a communication gap that makes it difficult to support high-level asset-generic decision making using quantitative tools. To overcome the communication gap and fully incorporate current and future data and analysis tools into TAM business processes, it is helpful to step back to summarize the existing constraints and requirements that drive cross-asset decision making.

1.1 NATIONAL AND AGENCY GOALS

Quantifying transportation system performance is a matter of developing a clear description of what customers and stakeholders want and value. These strategic values are stated in guiding documents such as MAP-21, the Moving Ahead for Progress in the 21st Century Act (P.L. 112-141), which was signed into law on July 6, 2012. This legislation sets national goals in 23 USC 150(b) as:

> *(1) SAFETY.—To achieve a significant reduction in traffic fatalities and serious injuries on all public roads.*
>
> *(2) INFRASTRUCTURE CONDITION.—To maintain the highway infrastructure asset system in a state of good repair.*
>
> *(3) CONGESTION REDUCTION.—To achieve a significant reduction in congestion on the National Highway System.*
>
> *(4) SYSTEM RELIABILITY.—To improve the efficiency of the surface transportation system.*
>
> *(5) FREIGHT MOVEMENT AND ECONOMIC VITALITY.—To improve the national freight network, strengthen the ability of rural communities to access*

> *national and international trade markets, and support regional economic development.*
> *(6) ENVIRONMENTAL SUSTAINABILITY.—To enhance the performance of the transportation system while protecting and enhancing the natural environment.*
>
> *(7) REDUCED PROJECT DELIVERY DELAYS.—To reduce project costs, promote jobs and the economy, and expedite the movement of people and goods by accelerating project completion through eliminating delays in the project development and delivery process, including reducing regulatory burdens and improving agencies' work practices.*

Individual agencies often list out their goals in legislation or strategic plans. For example, the Revised Code of Washington (State) lists the following policy goals for public investments in the state's transportation system (RCW 47.04.280):

> *(a) Economic vitality: To promote and develop transportation systems that stimulate, support, and enhance the movement of people and goods to ensure a prosperous economy;*
>
> *(b) Preservation: To maintain, preserve, and extend the life and utility of prior investments in transportation systems and services;*
>
> *(c) Safety: To provide for and improve the safety and security of transportation customers and the transportation system;*
>
> *(d) Mobility: To improve the predictable movement of goods and people throughout Washington state, including congestion relief and improved freight mobility;*
>
> *(e) Environment: To enhance Washington's quality of life through transportation investments that promote energy conservation, enhance healthy communities, and protect the environment; and*
>
> *(f) Stewardship: To continuously improve the quality, effectiveness, and efficiency of the transportation system.*

The Alaska Administrative Code lists the goals and objectives of the statewide transportation planning process as (17 AAC 05.125(a)):

> *(1) the economic vitality of the state;*
> *(2) the safety and security of users of the state's transportation system;*
> *(3) accessibility and mobility options available to people and for freight;*
> *(4) the integration and connectivity of various modes of the state's transportation system;*

(5) the preservation of existing transportation systems; and
(6) any metropolitan area plan developed under 23 U.S.C. 134 and 49 U.S.C. 5303-5306.

The Nevada Statewide Transportation Plan establishes a list of key performance objectives, or Guiding Principles, which guide the Department's construction and maintenance decisions. These include:

SAFETY – Improve safety for all modes of our transportation system.
CUSTOMER SERVICE – Improve internal and external customer service and satisfaction.
FISCAL RESPONSIBILITY – Secure the highest amount of funding possible for our state and ensure that it is invested responsibly and properly.
ASSET MANAGEMENT – Protect the public's investment in our transportation system.
MOBILITY / ACCESSIBILITY – Provide a statewide, multimodal, interconnected, efficient transportation system that enhances Nevada's Economic Competitiveness.
FREIGHT MOVEMENT – Improve the safety and mobility of freight movers.
ENVIRONMENTAL STEWARDSHIP – Ensure the human and natural environments are considered when developing the transportation system.

It can be seen that there is great commonality in goals across agencies:

- Many of these strategic documents reference statewide and metropolitan transportation plans.
- Practically all of them call for preservation of the existing transportation system or make other references to asset condition, and often call for minimization of the long-term cost of doing so.
- All of them list safety and/or security as a goal.
- Practically all of them list various aspects of mobility, including accessibility, travel time, congestion reduction, and reliability. Some of the documents emphasize both passenger and freight movement, general economic vitality, and intermodal connectivity.
- Most of these documents call for environmental sustainability.

Under the draft federal rules in 23 CFR 490, condition measures are specific to pavements and bridges, and do not address other asset classes. Other performance concerns aside from condition are defined more generically. However, language encouraging TAM Plans to "include all infrastructure assets within the right-of-way corridor" and to "support progress toward the achievement of the national goals identified in section 150(b)" (23 USC 119(e)) would indicate an intention that best practices in asset management would ultimately be extended.

1.2 GOAL-RELATED TERMINOLOGY

One of the difficulties in developing an interdisciplinary framework is in reconciling definitions of terms that may have evolved independently in multiple fields. In this report, these terms will be parsed somewhat more precisely than in much of the literature, in order to make clear some distinctions that are important in cross-asset tradeoff analysis. FHWA has been careful about the usage of these terms in its performance management rule-making, so this report will take its cues from the draft rules where possible. This section is not meant to be a complete glossary, but is meant just to highlight certain terms that will need disambiguation in order for the framework to be clearly understood and used. The rationale for these distinctions will become much clearer over this and the following two chapters.

1.2.1 ASSET-RELATED TERMS

The relations among these terms are illustrated in Figure **2**.

Asset – a distinct infrastructure facility of significant value, usually designed and built to serve a unique role in the transportation network. There are many definitions of the word "asset", but the scope of this report is limited to infrastructure assets in the highway right-of-way that comprise the transportation network. The discussion is further limited to the highway network, although the same principles apply to rail networks. Typically an asset is the primary unit of analysis for data collection, level of service standards, treatment selection, and procurement or construction.

Structure – a constructed asset designed primarily to carry loads, excluding pavements. Formally pavements are of course structures, but in this report a clear distinction is made because the data collection and performance characteristics of pavements, for asset management purposes, are generally quite different from all other structures.

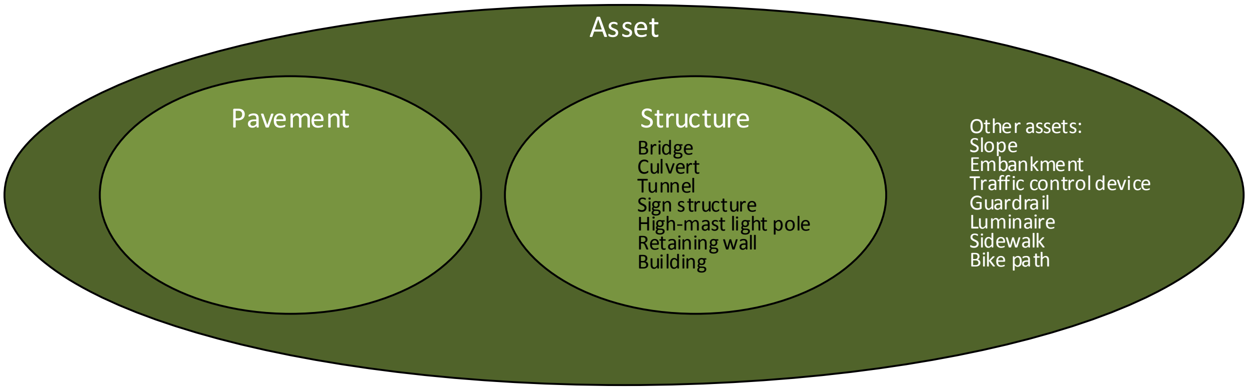

Figure 2. Venn diagram of assets addressed in this report, with examples.

Asset class – a broad population of assets having similar data requirements, program objectives, and management methods.

1.2.2 STAKEHOLDER-RELATED TERMS

The relations among these terms are illustrated in Figure **3**.

Road user – a person who uses, or wants to use, a specific asset that is to be managed, as a driver, passenger, bicyclist, or pedestrian. Certain measures may apply to persons or vehicles, so this will need to be made clear in context.

Non-user – a person affected by asset management decisions who is not a road user, such as a taxpayer, shipper, property abutter, elected official, lover of the environment, or user of a nearby road.

External Stakeholder – collective term for a user or non-user. Usually this term excludes agency personnel in the course of their duties, but in some contexts the term "internal stakeholder" clarifies that these persons should be included.

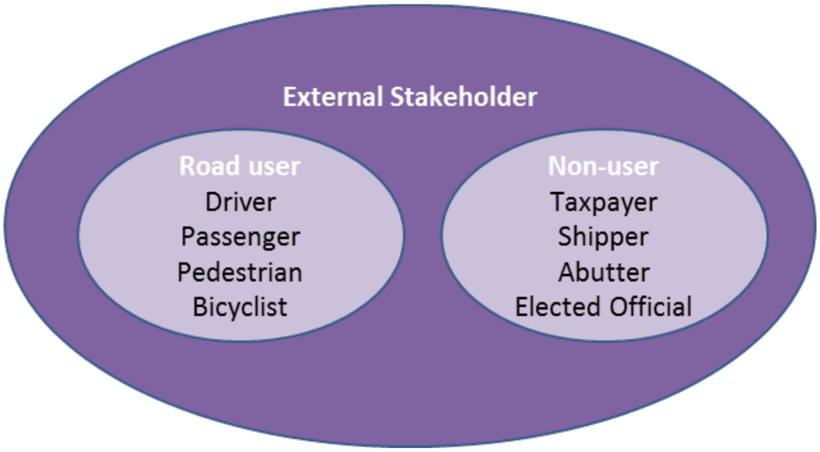

Figure 3. Venn diagram of external stakeholders addressed in this report, with examples.

Service Providers – often referred as internal stakeholders, this term primarily includes governmental transportation professionals at State, federal, regional and/or local levels, who establish policies, fund, regulate, manage, and operate roadway facilities at both network and asset levels . In other context, the term may refer private sector entities, such as public-private partnership concessionaires, who undertake or supplement the responsibilities of a public agencies in design, construction, operation, and maintenance of roadway facilities.

1.2.3 GOAL-RELATED TERMS

The relations among these terms are illustrated in Figure **4**.

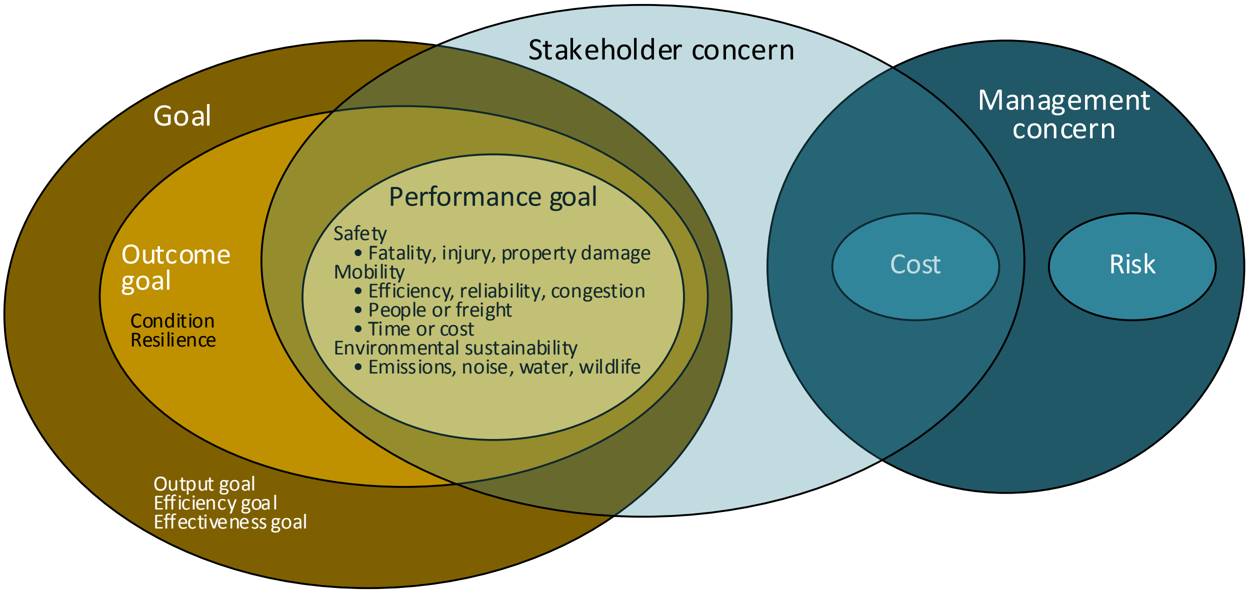

Figure 4. Venn diagram stakeholder concerns at the root of tradeoff analysis, with examples.

Goal – a desirable set of related transportation system physical and operational characteristics. This specifically includes the goals listed in 23 USC 150(b) and may include other goals.

Outcome goal – a goal that relates to durable properties of the transportation system, and excludes transitory characteristics of management processes. In 23 USC 150(b), this includes subsections (1)-(6), which are the topics of the performance management rule-making.

Performance goal – an outcome goal related to the utilization of the transportation system, directly affecting stakeholders. In 23 USC 150(b) this includes subsections (1) and (3)-(6).

Management concern – a set of transportation system properties that influence decision making but are not among the desirable properties listed as goals. Cost minimization and risk management are prominent examples discussed in MAP-21 and many state strategic plans.

Stakeholder concern – collective term for performance goal or cost, i.e., the durable concerns experienced by stakeholders. These are the main focus of the tradeoff analysis applications discussed in this report.

Mobility goal – a performance goal that concerns efficient movement of people and goods. In 23 USC 150(b) this includes subsections (3)-(5). While proposed federal rule-making focuses on travel time, travel cost may also be important to consider in decision making.

1.2.4 OBJECTIVES

Performance objective – A measurable aspect of a performance goal, to be maximized or minimized. Within mobility, for example, this may include travel time efficiency, travel time reliability, congestion, and vehicle operating cost, possibly divided by market segment (e.g. passengers vs freight).

Stakeholder objective – collective term for a performance objective or cost objective (initial or long-term cost)

Condition – a set of asset properties that deteriorate over time on every asset. Preservation action by the agency may be needed in order to offset deterioration and keep the asset in operation.

Resilience – a set of asset properties that affect the likelihood of service disruption due to unusual, unexpected events that do not occur on every asset. In the proposed framework this will be a key concept to facilitate the management of risk.

Measurable objective – collective term for stakeholder objective, condition, and resilience. Condition and resilience have unique roles in the framework because of their indirect but important effect on stakeholder concerns.

1.2.5 METRICS

Metric – a quantifiable indicator of performance or condition. The definitions of metric, measure, and target are directly from 23 CFR 490.101.

Measure – an expression based on a metric that is used to establish targets and to assess progress toward achieving the established targets (e.g., a measure for flight on-time performance is percent of flights that arrive on time, and a corresponding metric is an arithmetic difference between scheduled and actual arrival time for each flight).

Target – a quantifiable level of performance or condition, expressed as a value for the measure, to be achieved within a time period required by the Federal Highway Administration (FHWA).

Project benefit – In the proposed framework the benefit of a project is the combined positive impact on all stakeholder concerns, in comparison to a default or null alternative. This, in turn, depends on asset characteristics affected by the project, including condition, resilience, and utilization. Long term cost and risk play an important role in estimating the project impacts. Figure **5** illustrates the relationships.

Benefits can be defined and computed at multiple levels to satisfy different decision support needs, including benefit of a specific project, asset, or element; and generic benefits of classes of projects, assets, or elements.

Depending on decision making requirements, benefits can be expressed in terms of measurable attributes (e.g. IRI, element condition state, vertical clearance), in terms of condition states or indexes that combine attributes, or in terms of network attributes (e.g. total travel time, number of accidents, avoidable or avoided social cost).

1.3 STATEWIDE AND METROPOLITAN PLANS

As noted above, many states enumerate their strategic goals within their Statewide Transportation Plans. These plans often go further, to assign relative priorities to these goals (especially for preservation), or to list a set of planned implementation actions.

Statewide and metropolitan transportation plans often place a spotlight on localized or subarea problems that might not be fully reflected in the general agency goals, such as community aspirations, growth management, economic development initiatives, equity issues, operational strategies, intermodal coordination, inter-agency cooperation, and fulfillment of earlier commitments. These are more complex to evaluate in a resource allocation or priority setting analysis because by definition they do not treat every part of the network in a uniform way.

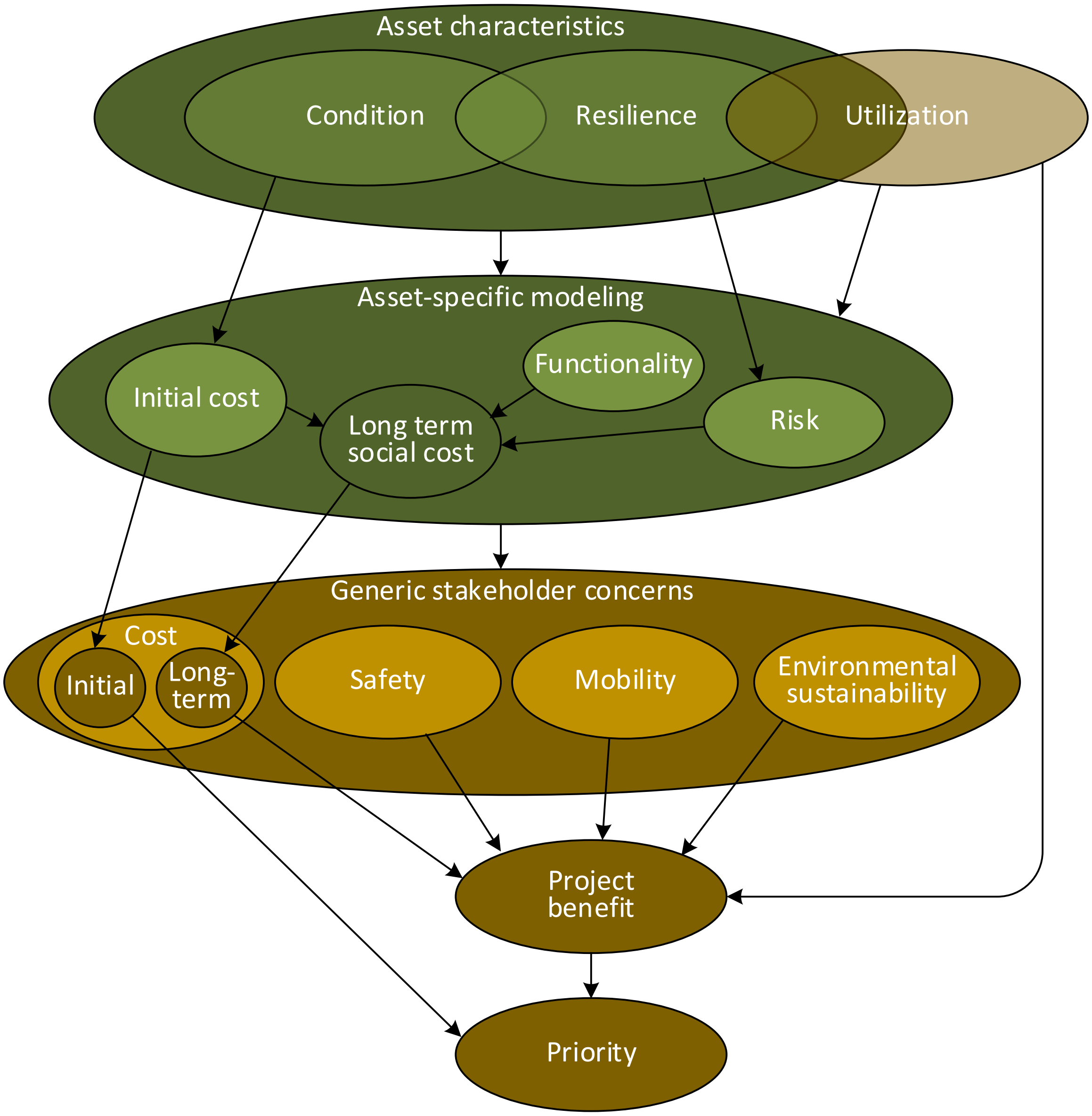

Figure 5. Conceptual relationships among the defined terms in estimating project benefits.

Many agencies explicitly omit capacity as a performance criterion in transportation asset management, but this is not universal. TAM practices in other countries often include the analysis of demand and its potential effect on congestion (Gordon et al. 2011). The proposed federal rules for system performance, freight movement, and congestion, just released in April 2016, strongly suggest a role for capacity and demand management alternatives as a part of TAM decision making (FHWA 2016).

A related issue is the high level of interest recently shown for strategies that substitute technology for capacity, or that use technology to manage demand. A few agencies, such as Nevada, have already deployed enough Intelligent Transportation System assets to justify their

inclusion within the TAM Plan. The performance characteristics of these systems are clearly very different from traditional highway facilities, and are not always well understood.
As agencies seek to stabilize and/or diversify their sources of funding, or adapt to funding shortfalls, new asset management alternatives may emerge. Infrastructure to support toll collection is expanding. Some agencies are reducing the target level of service on low-volume roads by withholding preservation work or reducing maintenance standards. This may ultimately lead to retirement of redundant links in the network. Municipal governments have been identifying sites where street capacity can be reclaimed for transit, bike, and/or pedestrian use.

1.4 TRANSPORTATION ASSET MANAGEMENT PLANS

"*The term 'asset management' means a strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the lifecycle of the assets at minimum practicable cost.*'' (23 USC 101(a)(2))

MAP-21 calls on state Departments of Transportation to prepare risk-based Transportation Asset Management Plans (TAM Plans) for the National Highway System (NHS) to "*improve or preserve the condition of the assets and the performance of the system*". The legislation mandates the establishment of condition and performance targets for at least pavements and bridges, and requires the TAM Plan "*to include strategies leading to a program of projects that would make progress toward achievement of the targets.*" Although only pavements and bridges are mandatory in the TAM Plans, states are encouraged "*to include all infrastructure assets within the right-of-way corridor in such plan*." (23 USC 119(e))

At the time of this writing, several state DOTs are gaining early experience in the development of these Transportation Asset Management Plans while others await the Final Rule. Nearly all of these early-adopter states are including assets other than pavements and bridges, and many are including assets that are not on the National Highway System. For example, Georgia has released a draft plan which includes highway signs; Minnesota is including certain drainage culverts, stormwater tunnels, sign structures, and high-mast light poles; Ohio is including culverts; Nevada, New York, Texas, Louisiana, and Alabama also are developing plans with a broader scope than NHS pavements and bridges, some of them covering all roads on the state highway network. These agencies have found that the structure of a Transportation Asset Management Plan can readily accommodate these additional asset categories.

All of the basic components of asset management and TAM Plans have been codified in various standards documents in recent years (Figure **6**). In the United Kingdom, the authoritative source is Publicly Available Specification 55, volumes 1 and 2 (BSI 2008). In the United States, a basic framework is described in a financial management context in Government Accounting Standards Board Statement 34 (GASB 1999), and in a strategic planning context in Volume 1 of the

AASHTO Guide for Asset Management (Cambridge et al 2002). A more detailed adaptation of the same principles is New Zealand's International Infrastructure Management Manual (IIMM, NAMS 2006). AASHTO has built on this concept in great practical detail with the AASHTO Transportation Asset Management Guide, Volume 2: A Focus on Implementation (Gordon et al 2011).

A key aspect of successful asset management implementation, brought out in the IIMM and the AASHTO Guide, is the notion of continuous improvement. A variety of human and automated ingredients need to be improved in tandem. The amount of progress that can be made in asset management tools is limited by the human and organizational readiness to use the technology, and vice versa. In a more tangible sense, the technology to produce quality asset management information depends on management willingness to accept asset management information in decision-making (and to see the value and pay the cost of producing this information); and management acceptance, in turn, depends on the quality of information that can be produced. A small improvement in the decision making process must be matched by an incremental improvement in technology, which then spurs the next small improvement in decision making.

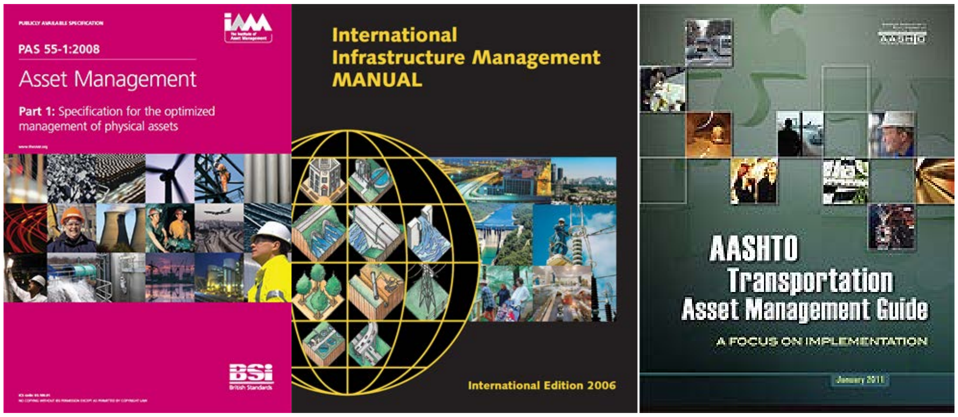

Figure 6. International asset management standards.

These same principles are widely used in the private sector, often taking the form of performance management frameworks such as the Balanced Scorecard and Six Sigma (Proctor et al 2010, Gordon et al 2011).

On 20 February 2015, FHWA published a Notice of Proposed Rule-Making (NPRM) to present its proposed regulations regarding the TAM Plan requirements (FHWA 2015). The NPRM specifies in Section 515.009(f) that the TAM Plan shall cover at least a 10-year period, shall be made easily accessible to the public, and shall establish a set of investment strategies that improve or preserve condition and performance in support of the national goals in 23 USC 150(b).

The regulation explicitly links the TAM Plan to the Statewide Transportation Improvement Program (STIP), which is the primary vehicle for programming of transportation projects.

Section 515.009(h) says “A State DOT should select such projects for inclusion in the STIP to support its efforts to achieve the goals” of the TAM Plan. In the commentary for Section 515.015, the NPRM suggests possible ways of explicitly tying STIP projects to the TAM Plan, including listing the projects in the TAM Plan itself, marking within the STIP those projects which are justified by the strategies in the TAM Plan, providing a list of such projects to FHWA under separate cover, or in a narrative within the STIP.

Section 515.009(d) lists the minimum content of the TAM Plan:

1. TAM objectives, aligned with agency mission;
2. Performance measures and targets;
3. Summary of asset inventory and condition;
4. Performance gap identification;
5. Life cycle cost analysis;
6. Risk management analysis;
7. Financial plan;
8. Investment strategies.

Many state DOTs use pavement and bridge management systems to develop much of the preservation component of the STIP. If the TAM Plan is to drive major parts of the STIP, then it must also feed back into the management systems to ensure a consistent linkage.

1.4.1 LONG TERM COST ANALYSIS

Section 505.007(a)(2) of the proposed federal rules specifies that the life cycle cost analysis in the TAM Plan is a quantitative network-level analysis that considers current and desired condition levels, asset deterioration, effects of adverse events, and treatment options over the whole life of assets.

The primary reason for including life cycle cost analysis in the TAM Plan and in the priority programming process, is the effect that project timing has on system performance and cost, especially for preservation work. Many common preservation treatments become feasible when condition deteriorates to a specified level. If the work is not performed in a timely manner, condition continues to deteriorate. This further deterioration may increase the needed quantity of work. At some point, further deterioration renders the preservation treatment infeasible, then necessitating a more expensive activity such as replacement. Thus, timely preservation prolongs asset life and reduces long-term costs.

This ability to delay replacement is valuable to the agency. In long term cost analysis, the benefit of preservation is computed using a discount factor, a multiplier applied to the delayed replacement cost for each additional year that the cost can be delayed. This is a highly standardized methodology used in nearly all asset management systems and many other types of financial analysis.

Preservation is an important part of any pavement or bridge program, but may be less significant for certain other asset classes, especially manufactured assets. Traffic control devices, for example, often do not have preservation treatments available for them. They are merely replaced when they fail to pass minimum operational standards (such as for retroreflectivity), or reach a recommended replacement age. It is important for cross-asset decision support to correctly evaluate the available alternatives according to the potential inter-temporal tradeoffs when they exist.

1.4.2 RISK MANAGEMENT

MAP-21 specifies that the TAM Plan shall be risk-based. In the proposed rules, Section 515.007(a)(3) elaborates that the TAM Plan must establish a process to identify the hazards affecting the movement of people and goods, assess the likelihood and consequences of adverse events, and evaluate and prioritize mitigation actions.

Transportation Asset Management practices nationwide are becoming more risk-based, because each state has its share of threats to transportation system performance. MAP-21 describes an expectation that risk analysis should be systematic, based on data and analysis. If the cause-and-effect relationship between hazards and service disruptions is measured, then the agency can begin to develop systematic strategies to reduce risk. Risk cannot be eliminated, but it can be managed.

Systemic risks. In Transportation Asset Management (TAM) Plans developed so far, most of the states have focused on systemic risks, affecting the agency or transportation system as a whole in a manner that is not site-specific. In this area, best practice has been to create a risk register listing the sources of risk and the agency processes created in order to manage the risk. Examples of such risks are:

- Uncertainty in federal and state funding;
- Inability to recruit and retain qualified staff;
- Market variations in labor, materials, equipment, and contractor prices;
- Insufficient competition in supplier markets;
- Potential damage and dislocation from climate change and sea level rise;
- Liability caused by ill-defined regulatory requirements;
- Poorly-defined internal policies and procedures leading to uncertain or inconsistent quality and cost of work;
- Uncertainty in the lead time and cost of regulatory compliance;
- Global uncertainty in the rates of deterioration of the various asset classes.

In most cases agencies are able to qualitatively define failure scenarios for these systemic risks expressed in terms of agency performance objectives. In some cases there is an effort to quantify, in general ranges, the likelihood and consequence of these scenarios. Minnesota DOT, in particular, has devoted considerable effort in this area.

Asset-based risks. Apart from systemic risks, there is another class of risks that is site-specific, where various natural or man-made hazards affect the ability of individual assets to satisfy agency goals. AASHTO's Transportation Asset Management Guide (Gordon et al. 2011) describes four categories of asset-based risk:

- Natural events and hazards such as earthquakes, landslides, storm surge, high winds, floods, scour, wildfire, extreme temperature, and permafrost instability;
- External impacts such as failure of outside parties to perform required services, or terrorism;
- Asset failures caused by systematic physical deterioration or unexpected failures, such as fracture of structures;
- Operational hazards such as overloads, over-height truck collisions, vessel collisions, or safety equipment failures.

Most of these hazards are being addressed in an upcoming guideline for bridge management being prepared under NCHRP Project 20-07(378). Some of them apply to all asset classes since they may affect roadway embankments as well as bridges.

Many state DOTS have made progress with asset-based risks, with the best-known tools and initiatives related to bridges in Florida and New York, and embankments and slopes in Washington, Alaska, and Colorado. These initiatives build on the concept of asset management as relying on data and analysis – that is, quantitative tools – to assess risk and to prioritize risk mitigation actions. While the specific data and tools vary by agency, asset class, and hazard, a common pattern can be seen:

- Failure scenarios are defined as generic, prototype events where one or more performance objectives for a given asset cannot be met for a period of time, because of a defined hazard.
- The probability of the scenario is estimated for each individual asset.
- The consequence of the scenario, if it occurs, is estimated for each asset, usually relying on asset-specific information such as asset size, utilization, and alternative routes or modes.

Consequences are quantified in measurable terms related to the performance goals such as condition, safety (potential changes in accident rate), mobility (delay and detours), environmental impacts (emissions and water quality), and long term cost. Some agencies create weighted scores from these performance measures, while others use standardized methods such as AASHTO's Red Book to convert all impacts to dollars.

1.4.3 FISCALLY-CONSTRAINED INVESTMENT ANALYSIS AND TARGETS

The section on investment analysis is the place where most TAM Plans are explicit about performance tradeoffs. If an agency is assumed to be operating at its best level of productivity, the outcome level of a performance objective is directly related to the amount of resources devoted to that objective. Agencies are required, by proposed federal rules, to produce condition targets for National Highway System pavements and bridges. Therefore, TAM Plans typically provide an analysis of the tradeoff between funding and condition in these terms. Figure **7** shows an example.

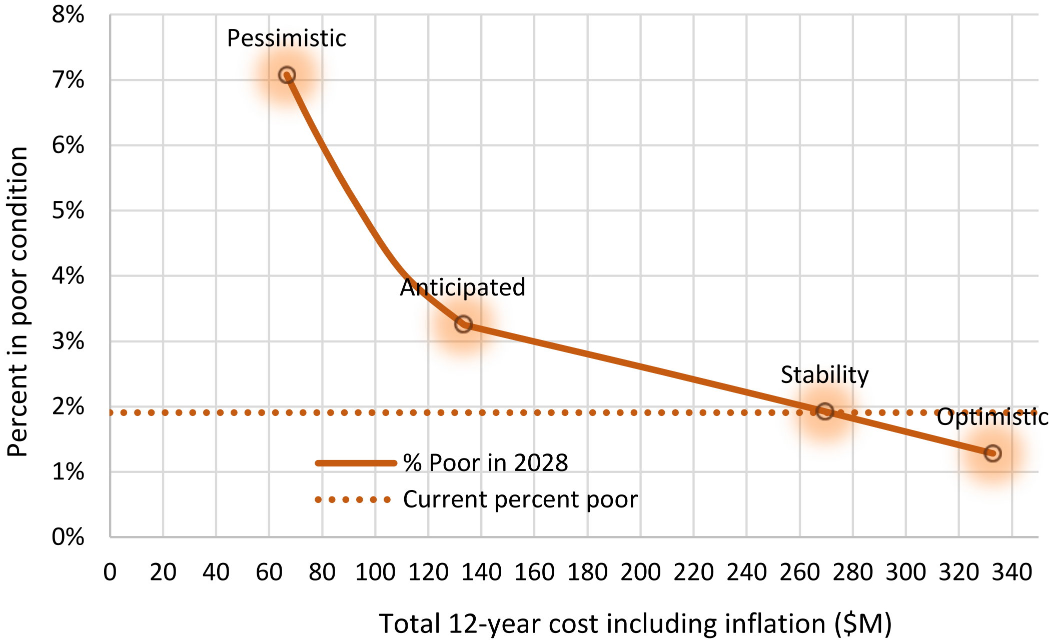

Figure 7. Example of tradeoff analysis, funding vs. condition.

More recent performance rules add measures for other performance objectives apart from condition, which may be addressed in future TAM Plans. If the agency is able to quantify more than the minimum condition measures, as most are, it is possible for TAM Plans to explore many more relevant tradeoffs. The value in doing so is the ability to gain a superior understanding of the potential effects of high-level decisions. Examples of relevant tradeoffs include:

- Capital vs maintenance;
- Tradeoffs among asset classes (e.g. pavements vs. bridges);
- Tradeoffs among performance objectives (e.g. safety vs long term cost).

In each case, the allocation of resources from one class of investments to another should affect performance outcomes: positively for the category receiving more resources, and negatively for the category receiving less. When multiple decision makers are involved, this kind of information can form the basis of a well-informed negotiation.

If key stakeholders in funding and policy decisions can be engaged to participate in this tradeoff analysis, the quality of decision making may be substantially improved. Historically agencies have found it difficult, however, to gain the necessary engagement. Time availability is always a constraint for decision makers. Often the technology gets in the way: the pavement management system might use different definitions of cost and benefit than the bridge management system; or stakeholders are discouraged by mathematical methods; or the methods are not able to consider important scenarios or constraints. There is a strong need for a standards-based approach, using relatively simple methods, so decision makers can focus on the key tradeoffs. That is a significant goal of the current study.

1.5 MAKING THE TAM PLAN MORE COMPREHENSIVE

As noted above, most of the agencies that have prepared draft TAM Plans so far have gone beyond the minimum federal requirements. This is an encouraging recognition of the scope of their responsibility and the potential benefit of improved decision support tools. The premise of the current study is that a large number of agencies will want to make their TAM Plans more comprehensive, and eventually federal requirements and/or industry standards might evolve in this direction. There are several directions that this evolution may take.

1.5.1 BEYOND THE NHS AND STATE SYSTEM

MAP-21 requires the participation of Metropolitan Planning Organizations (MPOs) in the TAM Plan process, and this has already happened in a number of states, especially Ohio and New York. Usually MPOs have little or no ownership or custodial authority over transportation assets, but they do have planning authority over parts of the National Highway System and the state-maintained highway network, which has provided a basis for cooperation.

If MPOs are able to participate in a meaningful way, some of the states have decided to extend the scope of the TAM Plan to locally-owned roads. Usually the local networks have the greatest problems with deferred maintenance, and local agencies may lack the technical expertise and resources needed in order to manage performance. The state agency, through the asset management process, may be able to contribute technical expertise efficiently (as it often does, for example, with bridge inspection), and the dialog may help in building strategies to address the resource shortfall.

Notwithstanding these good intentions, a significant barrier is that the state and local agencies have independent governance, widely varying stakeholder needs, and different plans and priorities. More prosaically, they may even differ in procurement decisions about data collection equipment and information systems. To make a cooperative inter-agency approach workable for asset management, a standards-based approach would be extremely helpful. Regardless of history, plans, and priorities, it would be desirable if a specific minimum set of performance measures could be standardized, and if key differences – such as relative priorities and corridor goals – could be made explicit, flexible, and easy to evaluate.

The comments received by FHWA on the January 2015 Notice of Proposed Rule-Making for performance measures, and the observed quick adoption by states of the proposed Good-Fair-Poor measures, would indicate that there is potential for further standardization. The ability to improve the management of local road networks would be a prime goal.

1.5.2 BEYOND PAVEMENTS AND BRIDGES

The most complete and uniform transportation asset inventory across the nation is the National Bridge Inventory (NBI), mandated by Federal legislation. Each state DOT is required to submit an update of this inventory to the Federal Highway Administration (FHWA) each year, for nearly all bridges of at least 20 feet in span that are open to the public, regardless of ownership. The contents of this inventory are specified by the NBI Coding Guide (FHWA 1995).
All state DOTs also have a pavement management inventory (Flintsch et al 2004), although this does not have the uniform nationwide coverage and is not compiled in a centralized national database as is done with the NBI. Other types of assets have less coverage in asset inventories.

Table **1** summarizes the percent of states found to have inventories and condition data for several types of assets, according to two recent surveys.

Table 1. Percent of agencies having inventory and condition of each asset type.

	% with asset inventory		% with condition survey	
Asset type	2007	2012	2007	2012
Signs	56	91	28	86
Guardrail		81		72
Traffic signals	78		35	
Drainage culverts	70	72	50	67
Roadway lighting	69	70	22	65
Pavement markings	61	60	42	63
Retaining walls		49		47
Sidewalks	31		18	

2007 is from (Markow 2007), 38 responses
2012 is from (Hawkins and Smadi 2013), 43 responses
Blank indicates results were not reported.

The table shows that sign inventories have become nearly universal in recent years, and other types of asset inventories are very common. The use of condition surveys increased dramatically over the five-year period for the asset classes surveyed. In addition to these assets, about half of the states are using a rockfall hazard rating system, which usually includes an inventory of roadside rock slopes for at least a portion of the network (Pierson and Turner 2012).

These are not necessarily complete statewide inventories. In most cases, inventories are limited to assets owned and/or maintained by the state DOT. They often are further limited to the state highway network or to particular corridors, districts, or functional classes. In most cases they are updated each year, but in some cases they are updated more often (especially for roadway lighting) or less (especially for sidewalks), or on a random schedule. Some have never been updated.

All of these asset classes could potentially be subject to condition and performance targets. Preservation programs often exist for culverts, sidewalks, retaining walls, and slopes, so long term cost analysis may be relevant in the determination of optimal preservation investment levels and timing. For other asset classes, such as signs, pavement markings, traffic signals, and lighting, it is useful to track performance at least in terms of the percent of the inventory (perhaps in the form of percent of assets, percent of road-miles, or percent of intersections) satisfying a level of service standard.

Throughout this report, all of these asset classes are considered in the methodology.

1.5.3 BEYOND CONDITION

Each asset class affects cost, risk, and performance in its own distinctive way. Typically considerations of condition and cost are basic to any pavement or bridge management system. But other performance concerns are also at stake:

- Pavement skid measurements are frequently recognized as affecting safety.
- Pavement roughness is modeled to affect travel speed and travel time in common planning models such as HERS-ST (FHWA 2005).
- Bridges are assessed for various types of risk, especially related to scour, fatigue, and advanced deterioration.
- Bridges are also assessed for characteristics that prevent truck use, such as weight limits or impaired clearances.
- Slopes, embankments, and retaining walls become management problems mainly because their failure can impact safety and mobility. This is often expressed as a risk management concern.
- Asset characteristics that affect mobility by forcing detours or delays, may also increase pollutant emissions, thus negatively impacting environmental sustainability.

Common ground among these performance issues consists of a uniform pattern of performance measures and a consistent system for assessing and comparing project benefits and costs. The goal areas specified in 23 USC 150(b), state legislation, and strategic planning documents generally provide a stable and comprehensive framework for evaluating all types of performance.

1.6 MANAGEMENT SYSTEMS

Most state transportation agencies use pavement and bridge management systems to support the implementation of their TAM Plans. These systems ideally have at least the following functions:

- Store, manage, and report on an inventory of assets. The data in this inventory typically include description, classification, location, jurisdiction, geometry, and history data.
- Store, manage, and report on current and past condition, based on a periodic condition survey. The management systems also typically include functionality for scheduling and managing the updating process for inventory and condition.
- Identify capital and maintenance needs on a given asset based on a set of standards or warrants, and based on current conditions and performance.
- Estimate costs and effectiveness of proposed work. Effectiveness is expressed at least in terms of condition, but may address other performance concerns as well.
- Predict future conditions and future demand, using this information to project future needs and their cost and effectiveness. One result is an estimate of long-term cost.
- Analyze the risk of service disruption caused by asset characteristics and hazards.
- Generate multiple scoping and timing alternatives for the needs on a given asset. Apply a set of business rules which constrain the range of alternatives to be considered.
- Compute a priority indicator which may address one or more aspects of performance. Report and manipulate a priority list of needed work in a given year.
- Apply budget constraints, identify the set of investments which maximize desired outcomes in a given year when the constraint is applied, and forecast future network level outcomes for condition and performance based on the selected investments.
- Assist in the development of fiscally-constrained performance targets.
- Support the allocation of resources among parts of the inventory, forecasting likely scope and timing of projects, and forecasting of future performance as affected by the resource allocation.
- Support development of preservation and risk management strategies.
- Support negotiation of funding levels and development of new funding sources.
- Assist in organizing capital and maintenance needs into projects, tracking the status of projects, and maintaining a history of completed work.

Not all management systems have all these functions. Even when the capabilities exist, not all agencies use them all. A barrier to implementation of the decision support capabilities in these systems is the siloed approach where, for example, bridge needs cannot be prioritized in the same list as pavement needs. Management systems encapsulate scientific aspects of data collection, deterioration, risk, and cost modeling that are truly specific to asset classes, as well as more generic capabilities, such as priority setting and resource allocation. The planning support features are helpful in providing a complete set of functionality to make use of the data, but many agencies find that the asset-specific approach to programming and resource allocation does not fit their asset-generic business needs.

To make management system analysis more useful, it would be desirable to have a set of standardized definitions of performance outcomes, that management systems can produce for work candidates within each asset class. These outcomes would encompass the major performance goals and concerns described above, including the 23 USC 150(b) goals, initial cost, long term cost, and risk. Management systems for pavements and bridges, and comparable tools for other asset classes, would each produce applicable outcome forecasts using the same set of definitions. Then a more generic system, perhaps a spreadsheet, could deal with cross-asset priority setting, resource allocation, and project development.

This approach is described in NCHRP Report 806 (Maggiore et al 2015) as the Pooled Project Set, and in the AASHTO Transportation Asset Management Guide, Volume 2 (Gordon et al 2011) as the Investment Candidate File. As depicted in Figure **8**, the Investment Candidate File gathers investment needs and alternatives from various systems into a common format using standardized definitions. A tradeoff analysis performed on this common list can then serve the various business processes of asset management in a non-siloed manner.

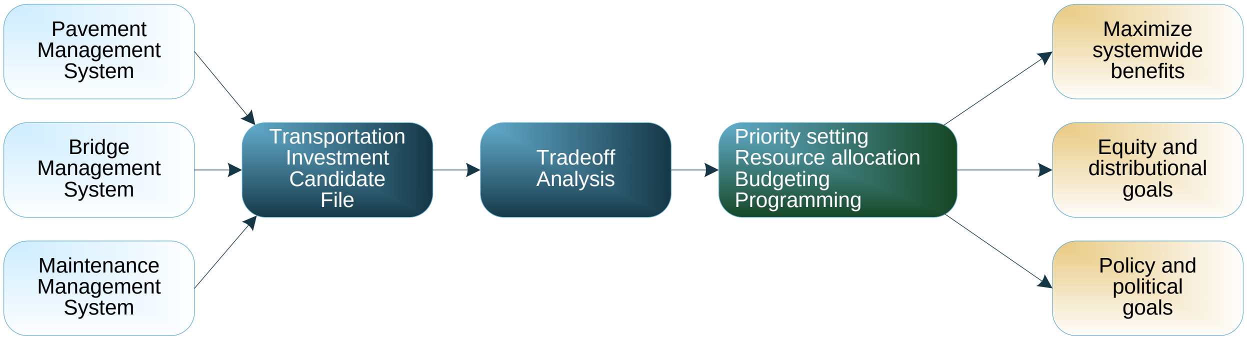

Figure 8. Structure of cross-asset tradeoff analysis (Gordon et al 2011).

Many agencies have an investment candidate file, but might not have fully explored its potential uses in cross-asset decision support. The file may be a part of a project management system, or a STIP database, or a shared spreadsheet. Since the time frame of the TAM Plan is much longer than that of the STIP, there is value in developing an interface with existing management systems and geographic information systems in order to manage the data, keep it up to date, and communicate its status. Table **2** shows a comprehensive overview of the data that may be needed to identify work candidates, connect to existing information systems, document estimates of cost and performance outcomes, support programming and resource allocation decisions, and support communications, all in an asset-generic way.

The Investment Candidate File will be a central feature of the methodology discussed throughout this document. While the file has a considerable amount of information, it is important to recognize what is *not* in the file: asset-specific physical condition data, deterioration and life cycle cost models, and risk assessment models. Such data are encapsulated in the separate management systems and are allowed to advance on their separate timelines in concert with industry advances in the state of the practice. The bottom-up perspective discussed in Chapter 4 will describe the necessary linkages between current asset-specific management systems and the generic Investment Candidate File.

For assets other than pavements and bridges, it is common to add such assets to an existing pavement, bridge, or geographic information system. The assets most commonly managed in this way are culverts, sign and light structures, retaining walls, and unstable slopes. For these assets, spreadsheets are by far the most common means of developing decision support information such as long-term cost analysis and risk analysis (Gordon et al 2011). A benefit of the architecture depicted in Figure **8** above is that agencies can develop data collection processes and analysis tools for each asset class on its own timeline, provided that compatibility is maintained with the Investment Candidate File.

Table 2. Contents of the investment candidate file (Gordon et al 2011).

Type of information		**Data items**	**Description**	**Purpose**
Identification		Project or work order ID Responsibility (organization or unit) Means of execution (contract, in-house, etc.) Desired/planned year Planning/delivery/workflow status	Identifiers here would feed into project tracking or enterprise resource planning systems where applicable.	Uniquely identify projects. Interface with related information systems. Support project development workflow.
Assets	For each cost object:	Identification Geographic location Jurisdiction Value Utilization	List the assets and/or policy concerns that are affected by the action.	Support mapping and reporting by geography and jurisdiction. Provide planned work status to asset management systems. Provide asset weighting in the computation of benefits.
Activity Drivers	For each activity driver:	Performance measure or deficiency Threshold level Actual level	Includes action warrants, level of service standards, vulnerability conditions, damage, or defects. Existing or forecast.	Document the direct justification of projects.
Activities	For each activity:	Classification Quantity (of output) Cost	Includes any type of activity within the scope of asset management: capital, maintenance, preservation, functional improvement, expansion, etc. Also includes engineering, mobilization, traffic control.	Describe the work to be performed and build up the cost estimate.
Resources	For each resource:	Classification Quantity (of input) Cost	Includes labor, materials, equipment, or contract pay items.	Interface with resource management to forecast staffing, stockpiles, and other resource needs.
Forecast Outcomes	For each performance measure:	Forecast change in performance Scaled change in performance Effect of advancement or delay	Includes measures of condition, life cycle cost, user cost, mobility, safety, reliability, comfort/convenience, externalities, risk, etc.	Forecast the performance resulting from the work, and compare with performance targets. Support performance based management.
Project Inter-Relationships		Projects that must be completed first Projects that can't be programmed together Projects that must be programmed together Projects that are mutually exclusive	Constraints on the scheduling and funding of work.	Ensure that traffic control plans are valid, that projects are compatible, and costs are fully recognized.
Evaluation		Total and incremental cost Total and incremental benefit Total and incremental benefit/cost ratio	Priority setting and budgeting criteria.	Set priorities, manage funding limitations.

1.7 NCHRP REPORT 806

National Cooperative Highway Research Program (NCHRP) Report 806 is the product of NCHRP Project 08-91 (Maggiore et al 2015). It describes a method for resource allocation using mathematical optimization, where the objective function is a measure of utility.

The prototype tool delivered with the report implements a "bottom-up" approach that is compatible with the structure described in Figure **8** above, for tradeoff analysis and the Investment Candidate File. Work candidates can be generated by separate management systems, evaluated for cost and performance outcomes. The tool provides a means of combining dissimilar performance outcomes, setting priorities, and allocating resources.

Report 806 also describes a "top-down" approach, but this approach is different from the strategic perspective discussed earlier in the present report. The approach relies on pavement and bridge management systems to generate cost vs performance curves, which it can use to allocate resources by equalizing a marginal benefit/cost ratio. Although not widely implemented, it is a feasible general approach to network-level tradeoff analysis, and will be discussed in more detail in Chapter 2.

1.7.1 DECISION SUPPORT TECHNOLOGY

Included within Report 806 is a package of software to demonstrate several decision support technologies that are meant to address parts of the asset management problem. These include:

Analytic Hierarchy Process (Saaty 2009). A panel of experts and/or decision makers are asked to complete a survey consisting of a set of pairwise choices among hypothetical alternatives. A procedure based on linear algebra is used to reduce the survey results to a set of criterion weights, reflecting the relative importance of various properties of the alternatives. The relative attractiveness of candidate investments is expressed in the form of a utility function which uses these weights and the differing properties of the various alternatives.

Integer programming (Woolsey 1998). Objectives and constraints on program management decisions are expressed in the form of linear equations, where the decision variable is a discrete choice from among two or more alternatives. An algorithm known as "branch and bound" is used in order to find a set of program choices which maximizes the utility function and satisfies the constraints. In general, the constraints can include funding limitations, performance criteria, and project interrelationships.

Non-linear optimization (Miettinen 1998). Since the network-level tradeoff between funding and performance is, in general, non-linear, the "top down" approach is solved using a non-linear gradient search algorithm. This optimization finds a point on each funding vs. performance curve, which together maximize utility subject to a set of constraints. The selected point on each curve then indicates the allocation of funding and the expected performance.

Genetic algorithm (Mitchell 1997). The funding vs performance curves required for the "top-down" approach are generated by a sorting algorithm. To avoid the potential for sub-optimal localized solutions, a genetic algorithm (a randomized search procedure) helps to constrain the solution space.

All of these technological tools are relatively intense, compared to the procedures normally found in management systems. Because of their complexity, they are typically used in a "black box" mode where decision-makers can specify inputs, and then wait to receive results. Only relatively sophisticated users of these tools expect to be able to interact with parts of the models and modify them to explore scenarios or to adapt the model to practical concerns such as corridor-level objectives and requirements.

1.7.2 LONG TERM COST

Report 806 notes that a limitation of the tools is that they do not allow for the possibility that delaying a recommended project might, because of further deterioration, render certain inexpensive treatments infeasible or might dramatically increase their cost. This is highly relevant in a preservation programming scenario where funding is limited, and thus a needed project may have to be delayed until funding is available.

The inability to model these inter-temporal tradeoffs is not an inherent problem with the Report 806 philosophy or general approach, but is rather the result of an implementation choice to exclude long term costs. The structure and definitions adopted in Report 806 make long term cost analysis difficult for several reasons:

- Cost is not easily constrained to a bounded range of values such as 0 to 100, so special care must be devoted to choosing appropriate definitions and methods to include long-term cost within utility functions.
- The report correctly suggests that the time scale and level of detail of condition and deterioration models found routinely in management systems, especially for bridges, would render computationally infeasible the selected technologies for decision support.
- Although long-term cost analysis is common in pavement and bridge management systems, and is mandatory under the proposed TAM Plan rules (515.007(b)), Report 806 does not address the possibility of making use of this information, extracted from management systems, within the recommended framework or tools.

All of these issues can be addressed by making appropriate changes to the framework and adopting simpler and more flexible technologies for decision support. NCHRP Report 590 (Patidar et al. 2007) explored this issue at length, by implementing a variety of alternative optimization tools, benchmarking and testing them, and identifying a set of choices that is much less limited by technology and by the human-technology interface. Later chapters of this report will describe this potential in much more detail.

1.7.3 RISK

A quantitative analysis of cross-asset resource allocation should consider all of the major performance goals of the agency, since different assets affect performance in different ways. Certain asset classes, especially embankments and culverts, traffic control devices, retaining walls, and unstable slopes, affect transportation network performance mainly through the risk of service interruption via asset failure. In these cases, the consequences of asset failure are felt by the public through losses in safety, mobility, environmental sustainability, or recovery cost.

Another opportunity for improvement in the Report 806 framework, therefore, is a more comprehensive treatment of risk. NCHRP Project 20-07(378) is developing a risk assessment methodology, focused on bridges, which is adapted from a methodology developed earlier for unstable slopes. The methodology begins by defining a set of hazards, and a set of scenarios where a hazard disrupts transportation service. This framework provides a structured way of estimating the likelihood and consequence of service disruption. Consequences are expressed in terms of stakeholder concerns so they take the same form as other performance impacts that are not related to risk. Later sections of this report will summarize the NCHRP 20-07(378) methodology and show how it can be adapted to all classes of transportation assets.

1.7.4 DECISION MAKING CONTEXT

Opportunities to improve on the Report 806 framework can be founded on a somewhat more refined vision of the decision making context. For example, the methods in report 806 are described as being intentionally very generic, so they can accommodate an unlimited range of performance measures. In practice however, as demonstrated above, the number of performance goals an agency may have is relatively limited. Moreover, the relationships between transportation assets and specific common performance goals have been explored extensively in the literature, providing a wealth of tools that may improve the quality of decision support.

Report 806 relies heavily on crowd-sourced judgment as a data source, when actual data and models are readily available and more consistent with the TAM philosophy. This report will describe how better use of research products and standards can simplify the application of judgment and make it more transparent and adaptable.

A related issue concerned with adaptability is the diversity of responsibility for asset management decisions. Many agencies decentralize portions of asset management decision making, and nearly all agencies have a functional division of responsibility (e.g. between planning and maintenance). Some aspects of decision making need to be guided by senior leadership and should remain consistent across the agency; but typically one purpose of decentralization is to allow different organizational units to focus more attention on the issues of greatest local importance. In the terminology of Report 806, the weights assigned to different performance criteria may need to differ significantly among parts of the agency. Weights may also change frequently with turnover in stakeholders, staffing, and current events.

This effect is magnified when multiple organizations are involved in decision making (e.g. MPOs and local agencies), and when transportation plans focus investment on specific corridors or specific types of traffic (e.g. freight routes). Often the importance of equity in outcomes and consistency with transportation plans may have significant importance beside the concern for consistent weighting of performance objectives.

In this more complex but realistic picture of the decision making context, it is very important to have responsive decision support tools that can adapt quickly to changes and can be fine-tuned easily to respond to a variety of needs. Much of the basic framework of Report 806 is perfectly appropriate, but some adjustments in structure and methods can make the methodology much more useful in the complex world faced by TAM decision makers.

1.8 SUMMARY: THE NEED FOR IMPROVED TRADEOFF ANALYSIS

The MAP-21 mandate for Transportation Asset Management Plans has been a watershed for improved infrastructure management practices, but a great deal of potential remains to be developed. Examination of existing draft TAM Plans, and observation of the processes used in developing these plans, reveals a number of issues that point to the need for better tradeoff analysis methods:

Cross-asset tradeoff analysis is necessarily multi-objective. Different asset classes affect performance in different ways. While pavement roughness is directly experienced by road users, cracking and other distresses often are not. Deficiencies in bridge operating rating or clearance affect trucks but might not affect smaller vehicles, and are unrelated to condition. Deficiencies in the resilience of roadway embankments might not affect road users at all unless a severe flood occurs. Meaningful cross-asset tradeoff analysis requires that project benefits be assessed consistently and fairly, which requires that all the significant performance objectives be considered.

Most relevant performance objectives can be measured in an asset-generic way. Condition is the only common performance objective that is necessarily assessed in a manner specific to asset classes. All other common performance objectives can be assessed in an asset-generic manner, and this includes the proposed federal performance measures in 23 CFR 490. Even condition can be summarized into an asset-generic form, such as a condition index ranging from 0 to 100, or a good-fair-poor classification.

Road users and stakeholders experience condition indirectly by means of other performance concerns. Advanced deterioration of bridge condition can increase long term costs if preservation becomes infeasible, can limit safety because of the risk of unexpected failure, and can limit mobility by means of load posting. Advanced deterioration of pavement can reduce comfort and speed, and thus mobility; and potholes or extreme roughness can cause vehicle damage or crashes. Other asset classes, such as culverts, unstable slopes, and traffic control devices, can also cause safety, mobility, and environmental problems if in poor condition.

Asset class silos are entrenched. Current draft TAM Plans contain elements that are asset-generic and other elements that are asset-specific. Inventory and condition data, and much of the quantitative analysis found in TAM plans (such as life cycle cost and investment analysis) are separately described for pavements and bridges, in most of the draft TAM Plans currently available. Many of the draft TAM Plans analyze a tradeoff of funding vs performance, but none address alternative allocations – and resulting performance outcomes – among pavements, bridges, and other asset classes. None of the existing TAM Plans demonstrate a linkage between the tradeoff analysis and actual decisions about resource allocation. In fact, most existing draft TAM Plans assume an exogenous pavement vs bridge funding allocation based on legacy federal funding allocations, which no longer reflect the current institutional environment.

Silos are useful, to a point. The technology of condition assessment is advancing rapidly. Pavements and bridges are advancing on parallel but independent paths, while at the same time methods for other asset classes, such as slopes, tunnels, and traffic control devices are coming into widespread use. Preservation and risk mitigation treatment methods, and forecasting models for condition and costs, are often asset-specific and also subject to rapid innovation. The silos are valuable as a way of focusing innovation and providing loci for continuous improvement. But the main focus of this report is that, at some point in the framework, the silos must all interface with an asset-generic set of processes, oriented toward stakeholder concerns, to complete the cycle of asset management (Figure **9**).

Focusing on condition perpetuates silos. Current pavement and bridge management systems, and the management practices surrounding these systems, focus on condition as the most influential measure of performance. Agencies have attempted to define generic condition measures such as condition index and good-fair-poor classifications. However, there is very little evidence of any attempt to align the definitions of these measures so they have a common meaning across asset classes. If an agency adopts 10-year condition targets of 4% Poor for bridges and 5% Poor for pavements, it would be valuable to know if these targets represent consistent consideration of long-term cost, safety, mobility, and environmental sustainability. Existing TAM Plans do not attempt to demonstrate this.

Asset-level risk management is not demonstrated in most TAM Plans. Many TAM Plans contain lists of systemic risks and general statements that such risks should be managed. Few, however, have adopted any methodology to measure each asset's contribution to risk, and the effects of such risk on network performance. There is great potential for improvement in this area.

This report will show that appropriate research and standards exist to vastly improve the state of cross-asset decision making. However, better and more focused tradeoff analysis tools will be required in order for agencies to put this work into practice. To ensure the feasibility of such tools, a set of standards is needed in order to define the interface between the asset-specific and the asset-generic. FHWA has already started on this in recent rule-making, but further evolution is possible in the next generation of performance measures and tools.

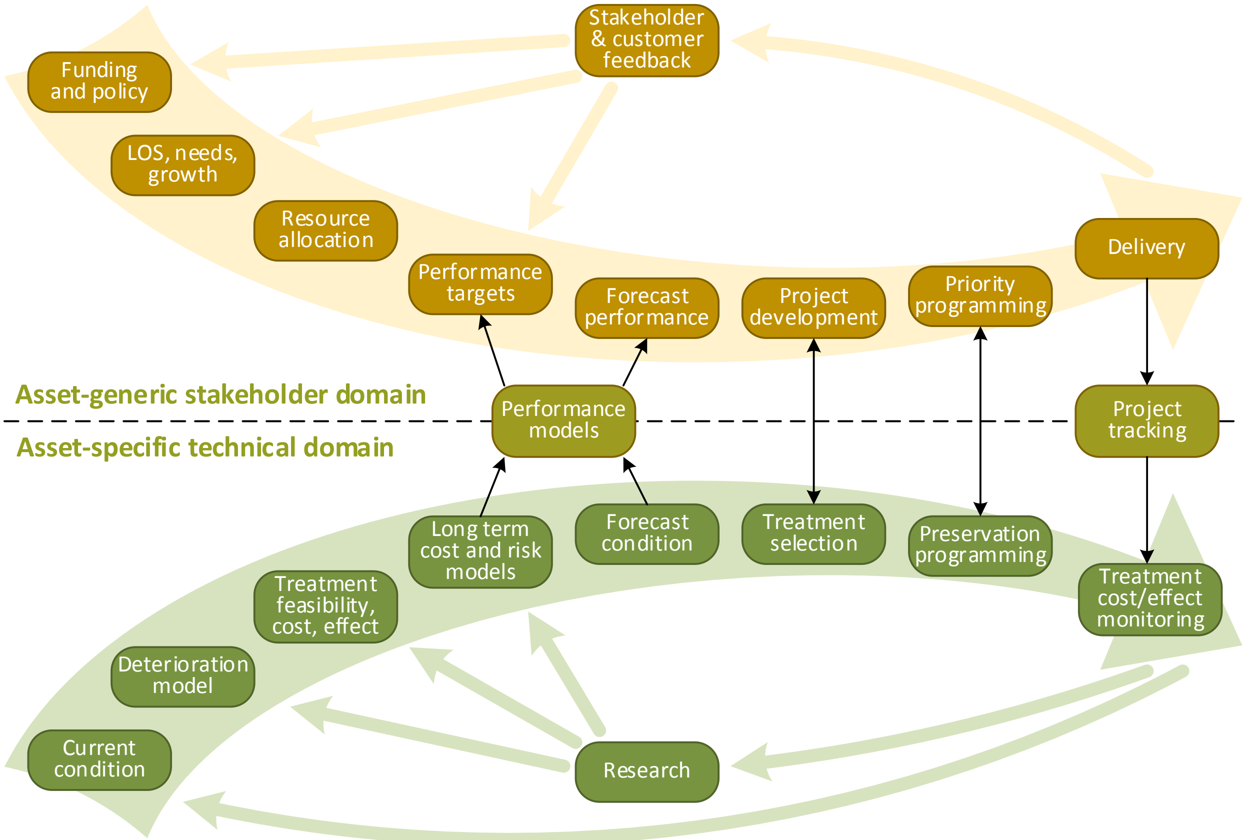

Figure 9. Interface between stakeholder and technical domains.

CHAPTER 2. APPLICATIONS OF TRADE-OFF ANALYSIS

Trade-off analysis is a key feature of transportation asset management because full accomplishment of aspirational objectives is generally not feasible within a limited timeframe and limited resources. Funding and staffing constraints, growth in demand, physical deterioration, environmental and land use constraints, project lead times, and non-transportation objectives all restrict the accomplishment of transportation objectives.
Often it is the case that changes in funding constraints may change the feasible range of performance outcomes: this is the funding vs. performance tradeoff. If funding is constant, changes in expectations for one performance concern may change the feasible range of outcomes for other performance concerns: this is the performance vs. performance tradeoff. Tradeoffs may also exist among geographic areas, levels of government, functional classes, market segments of road users, corridors and subnetworks.

Tradeoff analysis is performed for a variety of purposes: establishing performance targets, tracking and comparing performance, ensuring equity in outcomes, allocating resources, prioritizing projects, defining the scope of projects and programs, and negotiating with stakeholders over resources and expectations. Localized tradeoff analysis may be implicit or explicit in the development of transportation service plans and environmental reviews.

If it can be developed, a valuable agency resource would be a permanent systemwide tradeoff analysis that can be maintained by the agency, kept continuously up-to-date while allowing off-line scenario analysis, incorporating all of the agency’s infrastructure assets and performance concerns, and acting as a key input to the TAM Plan and STIP as well as a constraint on asset-specific management systems. This vision is explored philosophically in the following sections.

2.1 NETWORK LEVEL PERSPECTIVE

All tradeoff analyses involve comparisons among alternative futures that a decision maker might choose. The characteristics and structure of the tradeoff analysis depend on the business process for which the decision is to be made. In network-level Transportation Asset Management, the key business processes requiring tradeoff analysis include:

- Identification of long-term funding sources, each of which may have associated with it a set of long-range performance goals and constraints;
- Development of policies, which may govern agency delivery capabilities and productivity standards, data quality standards, the process of justifying and defining projects, the selection and weighting of performance objectives, the definitions of performance measures, and development of standard operating procedures.
- Allocation of resources among significant portions of the network over a multi-year timeframe. Resources may be allocated among networks (e.g. National Highway System vs off-NHS), among jurisdictions (e.g. state-owned vs locally-owned), among geographic areas (e.g. regions), or market segments (e.g. truck or transit routes).

- Intimately connected with resource allocation is the establishment of fiscally-constrained performance targets. There are several useful ways that these objectives might be expressed and used to guide decision making and to communicate performance and expectations.

All of these processes involve long-range decision-making, often beyond the normal time scale of accountability and management control. So funding and performance expectations are designed to have one or more near-term components or check-points, which represent opportunities to adjust course and update the longer-range expectations.

Transparency of the updating process is important as a means of demonstrating the quality of management and governance by demonstrating affirmative progress toward long-range objectives and stability of the rate of progress. Stakeholders and the public tend to have time-linear expectations, so performance measures that evolve in a linear fashion over time are easiest for most stakeholders to understand.

One distinctly non-linear aspect of tradeoff analysis is the Law of Diminishing Marginal Returns. Considering any specific objective of network performance, the agency has a wide range of possible expenditure levels that can be directed toward that objective, with a corresponding range of performance benefits. Each individual investment, such as a repair to a specific bridge, has its own unique cost and benefit. An agency seeking to maximize total network benefits will direct each marginal dollar to the investment that yields the highest benefit for that dollar. As a result, the first dollars return the highest benefits and later dollars return lower benefits. Across the whole network, the rate of return diminishes with increasing investment.

Figure **10** shows how this effect looks for an individual asset, such as a bridge. If the benefits of the various alternative candidate actions on a bridge are plotted against costs, the curve in Figure **10** is a typical result. If the scope of work on the bridge is upgraded from Maintenance to Repair, the additional cost is $350,000 and the additional benefit is $300,000, for a marginal return, or incremental benefit/cost ratio (IBC) of 0.86. Similarly, if the scope of work is upgraded from Rehabilitation to Replacement, the cost increases by $400,000 while the benefit increases by only $100,000, for an IBC of 0.25.

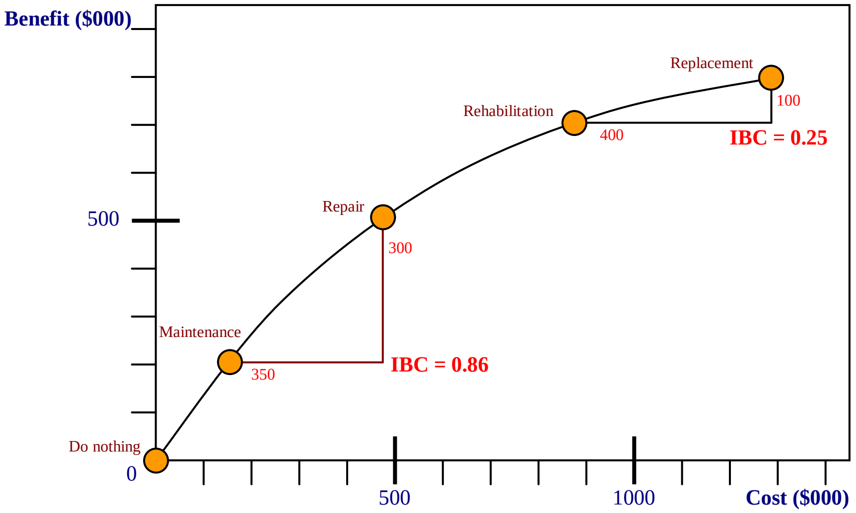

Figure 10. Example of diminishing marginal returns (from Patidar et al 2007).

To understand why this curve must always be concave downward, imagine a situation where Repair costs are more than Rehabilitation. If this were true, then Rehabilitation would have higher benefits at lower cost, so it would always be a more economical choice. Because of the competition in any real bridge inventory among a large number of investments, any Candidate that has benefits too low, or costs too high, to fit the diminishing marginal returns curve, will be less attractive than other investments on the same bridge or other bridges. Note that the curve does not always have to concave downward at the project level, where the condition of the asset indicates that rehabilitation could be a more cost effective option than maintenance.

When two or more portions of the network compete for funding, each has a benefit/cost curve similar in shape to Figure **10**. At any point, the slope of the curve is the incremental benefit to be gained from the next dollar of investment. The next dollar added to the overall program will maximize total benefits if it is directed to the portion of the network having the steepest slope at its current funding level. Adding that dollar moves the funding level of that part of the network slightly (by $1) to the right, where the slope is slightly less steep. If additional dollars are added, one at a time, at some point the slope will be less steep than that of another portion of the network, so additional dollars will then go to that alternative portion of the network.

Considering this logic over a large network, any level of funding generates the maximum benefit if it is divided among portions of the network in a way that equalizes the slopes of the benefit/cost curves. NCHRP Report 806 uses a non-linear optimization procedure to find the allocation that equalizes these slopes. In applying this type of methodology, however, several considerations must be taken into account:

- With multiple performance objectives, there may be different curves for different performance measures;

- Equalization of the incremental benefit/cost ratio of the curves is a concept not well understood by stakeholders. For some parts of the network, the investment level where slope is equalized might occur at a very low or very high level of performance. If the curve is very flat, a portion of the network might receive no investment at all. Stakeholders might find these outcomes to be inequitable.
- Different stakeholders and different agencies (in a multi-agency scenario) may value performance in different ways, so they might not agree on the shape and parameters of the benefit/cost curve.
- In an effort to please as many stakeholders as possible, decision makers will want to make use of the time dimension to show that all portions of the network receive investment and/or attain an acceptable level of performance over a sufficiently long period of time. The allocation of resources will therefore vary from year to year.

An important practical consideration is that dollars are not, in actual program delivery, allocated one dollar at a time. Rather, the allocation in practice is project-by-project. Thus, while network-level tradeoffs can be idealized and communicated using smooth benefit/cost curves, agencies may wish to develop them using the same project-level and program-level methods they use for the STIP and in their asset management systems, which may make it easier to understand how near-term decisions about projects and priorities affect longer-range objectives.

2.2 PROJECT LEVEL PERSPECTIVE

Individual assets may have a set of alternative investments which vary in both scope and timing. The alternatives will form a benefit/cost curve similar in shape to Figure **10**, but this curve will vary from year to year and from asset to asset. In TAM decision making focused on capital investments, it is common that routine maintenance activities are omitted, and larger preservation activities are infrequent. For example, Florida research found that preservation actions within the scope of a bridge management system can be expected to occur about once every 20 years on average on a given bridge (Sobanjo and Thompson 2011).

In a given year, the scoping alternatives available for a given asset may respond to different performance concerns. A bridge preservation project, for example, might improve condition and reduce long term costs, but have little or no impact on safety or mobility. A separate alternative might include scour mitigation, which reduces the risk of failure and, in so doing, increases long-term mobility by reducing the probability that the transportation link might be broken. The preservation and risk mitigation work might be performed together or separately. It would be unusual to address separate needs in separate years on the same asset in the same program horizon, because of mobilization and traffic control costs, and some management systems assume that this never happens. If the cost of preservation and risk mitigation is sufficiently high or not sufficiently effective, the agency may wish to consider total asset replacement, with greater costs and benefits across all performance concerns.

In most cases, incremental benefits are understood as the improvement in network-wide performance caused by an incremental expenditure to complete a project. This distinction is important for several reasons:

- If a project is implemented, its cost is removed from the funds available for other investments anywhere on the network. Since the opportunity cost is a network-wide impact, the benefits should also recognize all impacts network-wide.
- Assets can vary widely in size, especially bridge assets. Bigger assets cost more to build and repair, and have higher long term costs. The fact that a big bridge was built, is considered to be reflective of the value of the structure to the overall network. For example, a big bridge might serve a large number of vehicles per day, or enable a large reduction in travel time. Big costs yield big benefits in a benefit/cost curve such as Figure **10** above.
- Multiple assets may be combined into a single project. In order for total costs and total benefits of a project to be additive, they need to be computed under the same set of assumptions.

The practice of combining multiple assets into projects is often done in order to coordinate traffic impacts of work zones, or to capture economies of scale related to haul costs, material preparation, or other mobilization issues. For example, a group of assets may be combined into a large project in order to make efficient use of a new concrete mixing plant.

Assets other than pavements, bridges, and tunnels are often grouped with more expensive assets, or grouped together on a road segment, intersection, or corridor basis. In that subsidiary role it is relatively unusual for individual small assets to drive the scope or timing of the larger project. If the implementation year of a project is changed, the scoping alternatives, costs, and benefits may also change. Preservation work, in particular, is typically feasible only when assets are in sufficiently sound condition. If too much deterioration takes place (section loss in a steel girder, for example), preservation might no longer be an effective investment, and more expensive action may become necessary. In the case of risk mitigation actions, traffic volume may determine the number of people exposed to a hazard. If traffic on a specific road is growing at a rapid rate, the rapid increase in risk exposure may justify higher priority for that activity, compared to lower-growth roads having similar concerns.

In addition to general concerns about priority, project timing is also constrained by practical concerns such as project readiness (funding, planning, environmental review, design, land acquisition), competition for scarce resources (staffing, materials, contractors, specialized equipment) and the network effects of simultaneous work zones in multiple locations. These concerns not only affect the availability of near-term project alternatives; they also affect the range of feasible performance outcomes.

2.3 PROGRAM-LEVEL PERSPECTIVE

A comprehensive TAM Plan is a network level document, but implementation of the plan occurs through project level activities. Reconciliation of the network and project levels is done by means of a programming process. This overall process ideally covers the same timeframe as the TAM Plan, typically ten years, making it possible to verify that project level activities can lead to accomplishment of the performance targets proposed in the TAM Plan. However, project level commitments are required to appear only within the STIP, which covers a shorter time frame.

In the bridge management system used by several Canadian provinces, where similar timeframes are used, an integrated priority list of projects is developed for years 6-10, without further attempting to specify an implementation year (Ellis et al 2008). Only the first five years of projects are specifically associated with proposed implementation years. Although this innovation is not known to be used anywhere in the USA, it would be feasible under the federal rules and may help to simplify the transition of extending the programming process to ten years in agencies where this is not currently done.

In practice, the programming process is quite dynamic, even if a specific STIP project list is only published once a year. Project-level activities associated with inspection, project definition, identification of funding sources, environmental reviews, and design all cause changes to the program while it is under revision. Network-level activities such as financial planning, budgeting, bonding, and monitoring of market conditions also cause frequent changes.

It has always been the case that program management staff monitor changes in the program to ensure that plans reasonably match funding, allowing for a certain degree of over-programming to ensure that project delays do not cause loss of funding. With TAM Plans in place, agencies will also need to be able to check performance outcome forecasts against targets. This will require a higher level of integration of program development activities with asset management systems.

Under the architecture described above in Figure **8** and Table **2**, the core of the TAM programming process would be the Investment Candidate File, which contains all of the scoping and timing alternatives that are potentially implementable. Each candidate would include a set of outcome forecasts matching the target date published in the TAM Plan, usually 10 years in the future. The workflow status of each candidate indicates a published implementation year (as in the STIP) or a preliminary year based on forecast constraints or planning scenarios. The performance forecasts would then be aggregated to compute a forecast of network performance, using the same performance measures that are published in the TAM Plan.

If any of the forecasts do not attain the TAM Plan target performance, then program managers will want to make adjustments in the program to overcome the performance gap. This is an activity that few agencies have had to perform in the past, but it is implicit in an agency commitment to attain a set of TAM Plan performance targets. Small proactive adjustments made from year to year offer far more control over performance outcomes, than large adjustments made later. If an agency shows steady improvement in performance without having to make frequent changes in targets, this communicates active management of performance and builds confidence with stakeholders.

A frequent concern that has long been expressed in transportation agencies about management systems and TAM performance targets, is a lack of confidence in performance forecasts, especially in deterioration models. This perception has been a systemic risk factor which has been a significant barrier to implementation in many agencies. A capability to manage ten-year performance outcomes from year to year would be a risk management tool that might enable an agency to feel more comfortable adopting proactive TAM practices.

2.4 EVALUATING TRADEOFFS

As agencies work to develop their first TAM Plans, a big question on their minds is how to evaluate the acceptability of ten-year resource allocations and performance targets. There are at least two perspectives on this:

- Evaluation of **outcomes**. Agencies may evaluate whether performance outcomes are as high as possible; costs are as low as possible; distribution of resources and/or outcomes is equitable; state/metropolitan service plans are supported; and targets appear attainable given the level of uncertainty.
- Evaluation of **process**. Agencies may evaluate consistency of prioritization (e.g. consistent weights are given to the various performance objectives); acceptability of the preference structure used; and degree to which new needs are incorporated.

In a way this is a false dichotomy, because in practice both perspectives are important. The NCHRP Report 806 framework primarily relies on the process perspective, because the establishment of performance weights is a separate activity from network and program development. The activity of eliciting judgment and converting this to a preference structure is formal and time-consuming, so it is not easily repeated or updated during the program development process. A valuable improvement to the Report 806 methodology would be a framework that permits a more dynamic, but still accountable, way of adapting the preference structure to a complex and changing set of real-world requirements. This would enable decision makers to evaluate outcomes, and then adjust the relative weights of performance measures for parts of the network in order to achieve the necessary outcomes.

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CHAPTER 3. DEVELOPING CROSS-ASSET PERFORMANCE MEASURES

Transportation Asset Management decision makers face a set of competing stakeholder objectives as they seek to develop policies, programs, and projects. In this context, the major concerns are typically:

- Cost (initial and long-term)
- Safety
- Mobility (passengers, freight, or both)
- Environmental sustainability

Additional concerns that sometimes appear in strategic plans may include security (often considered as a part of risk), comfort (often converted to speed and then travel time), economic development, and property values. Reliability of travel time is typically considered as a part of mobility and more specifically as a part of travel time, measured as the amount of extra time that a typical road user would allow to ensure an on-time arrival (Cambridge 2014).

Condition is important in tradeoff analysis within the technical domain, for making comparisons among assets and with standards, and for tracking outcomes over time. Generally, however, condition affects stakeholders by means of the other performance concerns listed above. On the other hand, there are aspects of safety and mobility that are not related to condition. For example, a bridge constructed with inadequate vertical clearance or inadequate design load limits the passage of certain trucks, even if in excellent condition. Similarly, guardrails constructed to older standards may fail to provide full protection from severe injury in crashes. Traffic growth over time may lead to increased congestion and reduction in mobility and safety even if good condition is preserved. It is useful to track measures of asset condition because condition always deteriorates with age and usage, and agency action is inevitably necessary to offset deterioration and sustain a state of good repair. However, a full accounting of performance should address the stakeholder objectives, since assets affect these objectives by other means in addition to condition.

3.1 CHARACTERISTICS OF PERFORMANCE MEASURES

A wide variety of performance measures are used in asset management, but each measure is generally created with specific purposes in mind (Van Hecke 2014). This is important, because once the agency’s objectives are known and the business process is described, the number of relevant measures becomes much smaller. It is for this reason that the recommended framework starts from strategic decision making requirements, in a top-down manner, to determine what measures provide the most useful insight. The framework then goes on, in Chapter 4, to identify the data and analysis methods available to compute the desired measures.

NCHRP Report 551 (Cambridge et al. 2006) provides valuable context for this approach. It recommends the following criteria for performance measure selection:

- **Policy-driven**: Sensitive to policy objectives and conveys meaningful information about the transportation system.
- **Strategic**: Able to be forecast, relates to economic and technical information, and reflects time-dependent changes as well as the outcome of agency actions.
- **Consideration of options and tradeoffs**: Sensitive to relevant agency choices, applicable to “what-if” analysis, can be linked to resource availability, can provide a program-level or network-level perspective as well as project or asset-level.
- **Based on good information**: Produced by routine business processes and tools, can be aggregated or transformed to inform decisions at multiple levels of the agency, has realistic and feasible data requirements, relying on quantitative measurement where possible.
- **Feedback**: Provides useful understanding of problems and solutions for agency decision makers and outside stakeholders as needed, can be monitored and updated periodically.

An important aspect of these criteria is that a performance measure can have multiple facets in the way it is defined. It may have a general or intuitive definition, which is used in communications with senior leadership and stakeholders; an economic definition, relating to selection of actions or costs; and a technical definition, describing how it is to be calculated from quantitative data. Examples will be presented in Chapter 4.

Since the TAM business processes to be supported by this methodology relate to the performance of the transportation system, the methods focus on outcome measures, measures which describe the degree to which the agency meets its stakeholders’ objectives. This is distinct from:

- Output measures, describing the amount or quality of agency activity;
- Input measures, describing the resources used by the agency in its activities;
- Efficiency and productivity measures, relating outputs to inputs;
- Effectiveness measures, relating outcomes to outputs.

While all of these measures are important to effective management of a transportation agency, the problem of cross-asset decision making primarily affects the way outcomes are measured, and secondarily the way effectiveness is measured. This report therefore focuses on outcomes.

3.2 RELATING PERFORMANCE MEASURES TO THE DECISION MAKING CONTEXT

From the decision perspective, the relevant cross-asset performance measures relate to the choices available to a decision maker in each TAM business process. Certain types of decisions may be siloed to specific asset classes, especially in the domain of treatment selection policy. For example, development of ideal pavement overlay policies may depend on a life cycle cost analysis of pavements which is not dependent on decisions about any other asset class. Other decisions are more likely to require cross-asset performance measures.

Table 3 is a summary of the performance measures generally required for the most common agency objectives and decision making processes. The purposes of each decision determine which performance measures are most relevant. Important cross-asset considerations include:

- Performance expectations should be consistent across assets, especially when considering what constitutes “acceptable”, and in the expression of performance targets.
- Criteria applied to individual assets should be readily measurable.
- Project benefits need to be additive across asset classes and must not double-count the effect of condition.
- Project benefits describe performance of the network and take into account all affected assets and all affected road users.

Table 3. Decision context for performance measures.

Long-term funding and policy	
Purposes: • Design policies to maximize performance • Describe funding program objectives in measurable terms	• Condition index or percent by condition state • Frequency of specific condition deficiencies • Resilience index or percent by resilience state • Likelihood of specific hazard scenarios • Consequence of specific hazard scenarios • Initial project cost • Agency long term cost • Excess travel time (aggregate or broken out by market segment and/or cause) • Excess vehicle operating cost (aggregate or broken out by market segment or cause) • Excess accidents (actual or modeled) • Forecast emissions (aggregate or broken out by pollutant)
Acceptable levels of service	

Purposes:
• Decide whether a given asset should be counted as sufficient or deficient
	• Minimum tolerable condition
	• Minimum tolerable resilience
	• Asset-specific criteria:
	    • Minimum tolerable IRI, rutting, faulting
	    • Minimum tolerable operating rating, clearance, roadway width
	    • Guardrail impact standards
	    • Retroreflectivity or legibility standards
	• Minimum traffic level of service
	• Excess travel time as a percent of normal or desired
	• Accidents per vehicle-mile traveled
	• Maintenance cost as percent of replacement cost

• Needs identification – action criteria	

Purposes:
• Decide whether a specific action or class of action is feasible
	• Condition state
	• Resilience state
	• Asset-specific criteria:
	    • Cracking or rutting criteria
	    • Minimum tolerable operating rating, clearance, roadway width
	    • Slope or embankment geological characteristics
	    • Guardrail impact standards
	    • Retroreflectivity or legibility standards
	• Travel time savings as percent of normal
	• Modeled savings in accidents per VMT
	• Project benefit (based on long-term agency cost, user cost, or both)
	• Project benefit/cost ratio

Table 3. Decision context for performance measures.

Optimal project scoping	
Purposes: • Select optimal treatment on each asset • Decide composition of multi-asset projects • Identify down-scoping alternatives	🟩 • Direct agency cost 🟦 • Indirect agency cost (mobilization, traffic control, engineering, land, demolition) 🟦 • Agency long term cost 🟨 • Long-term user cost (time, operating cost, crash costs, out-of-pocket costs) 🟨 • Long-term likelihood and consequence of hazard scenario 🟨 • Project benefit (based on long-term agency cost, user cost, or both) 🟨 • Benefit increase relative to alternative of doing nothing during the program horizon 🟨 • Project incremental benefit/cost ratio

Priority programming and resource allocation	
Purposes: • Schedule projects to maximize goals within annual fiscal constraints • Meet the most urgent needs first • Develop the STIP	🟦 • Project cost 🟨 • Project benefit as avoidable social cost 🟨 • Benefit increase relative to alternative of one-year delay 🟨 • Project incremental benefit/cost ratio

Performance targeting and tracking	
Purposes: • Set performance expectations • Track progress toward objectives • Describe historical performance • Compare performance among assets	🟩 • Condition index or percent good or poor 🟩 • Resilience index or percent good or poor 🟨 • Excess travel time divided by normal time 🟨 • Excess travel time divided by VMT, or as percent acceptable 🟨 • Modeled or actual crashes per VMT, or as percent acceptable 🟨 • Modeled or actual emissions per VMT, or as percent acceptable 🟨 • Percent acceptable

Key:
🟩 Asset-specific, single objective
🟦 Cross-asset, single objective
🟨 Cross-asset, multi-objective

All of the asset-specific, single-objective performance measures concern condition or resilience. Condition includes a standardized and measured set of material defects that tend to deteriorate gradually and predictably over time on every asset. If allowed to deteriorate far enough, service objectives such as safety and mobility may be adversely affected. Agencies use preservation actions to try to prevent service impacts and to minimize the long-term cost of maintaining service. Condition is typically monitored in considerable detail, distinguishing significant distress mechanisms (such as corrosion and cracking) and often dividing each asset further into elements that have their own distinctive deterioration, treatments, and costs (such as bridge girders and expansion joints). When broad coverage is required over a widely diverse class of assets, such as bridges, conditions are typically assessed visually and classified into condition states. When distresses are less diverse and can be measured by automated means, scalar measures such as International Roughness Index are typically used. Either type of metric may be aggregated and summarized as a condition index, usually expressed on a bounded scale where 100 is best and 0 is worst.

Resilience includes a standardized and measured set of asset characteristics, which may or may not include condition, which affect the likelihood of transportation service disruption in the event of a hazard event, such as a flood, earth movement, or truck collision (Thompson 2016). The disruption event is infrequent and unpredictable for individual assets and does not affect all assets. Examples of resilience measures include:

- For rock slopes, the height, distance from road, geological character, condition, and mitigation effectiveness determine the likelihood that a rockfall event will disrupt service.
- For bridges, roadway vertical clearance (on or under), and truck traffic volume, determine the likelihood of an over-height truck collision with the bridge, which may disrupt service and damage or destroy the bridge.
- For traffic signals, age of equipment may affect the probability of failure, which may affect the likelihood of an intersection collision or an incident of degraded capacity.

Agencies attempt to manage risk by installing mitigation measures, such as rockfall fences, over-height warning devices, or newer signal components. When broad coverage is required over a widely diverse class of assets, such as rock slopes, resilience is typically assessed visually and classified into resilience states (Pierson and Turner 2012, Beckstrand et al. 2016). When characteristics are less diverse and can be measured by automated means, scalar measures such as vertical clearance, age, or pavement skid number are typically used. Either type of metric may be aggregated and summarized as a resilience index.

As discussed earlier, condition affects stakeholders indirectly by means of stakeholder concerns such as long term cost, safety, and mobility. Similarly, resilience also affects stakeholder concerns. In Table 3, condition and resilience are useful for decisions involving the direct comparison of an individual asset against a set of measurable criteria. This is the case for many types of policies, for levels of service and action criteria, for making comparisons among assets or groups of assets, and for tracking assets over time.

For business processes where the combined effect of multiple objectives is important, multi-objective performance measures are needed. This is especially useful for making a determination of cost-effectiveness, for comparing project or policy alternatives of diverse scope and impact, and for setting priorities. There are differences among business processes in how these measures are used, particularly in the definitions of the alternatives which are to be compared. The following sections explore these decision making requirements in more detail.

3.3 LONG-TERM FUNDING AND POLICY

In terms of the most frequently-used performance objectives, agencies will typically seek to minimize long-term costs within each asset class, and maximize safety, mobility, and environmental sustainability across asset classes. If these performance objectives are considered separately, performance can be expressed as direct outcome measures such as condition, excess travel time, forecast accident rates, and forecast emissions, especially if the long-term goals are expressed in terms of the current state of the network (e.g. “no increase in travel delay” or “10% crash rate reduction”).

If the ideal or minimum acceptable performance level for each objective is unknown or variable, then it becomes necessary to perform a tradeoff analysis across performance objectives. This then requires that relative weights, explicit or implicit, be developed to define a correspondence among the goal areas. One way to do this is to poll a group of decision-makers, stakeholders, and/or experts to estimate a set of relative weights directly, or to process them by some analytical means such as the Analytic Hierarchy Process used in NCHRP Report 806. This entails asking for opinions about the relative value of travel time vs accidents vs pollution vs long term cost.

There are a number of objections to this approach:

- These opinions are personal and subjective. Unless care is taken to select a panel representative of the broad range of customers, the opinions are likely to be biased toward the preferences of an elite group.
- Ultimately funding levels depend on taxation rates, appropriations, and other decisions that are in the political realm. Therefore the opinions of political leaders are of disproportional importance. It would be difficult to gather political opinions of this sort and such opinions are not likely to be stable over time.
- Appropriate weights may vary for different parts of the network, and may require separate but overlapping groups of stakeholders.
- There is constant turnover of stakeholders. New stakeholders might not accept a previous determination of weights if they were not involved in deciding the relative priorities.
- Objective measures are available for some aspects of the tradeoff analysis, based on research and standards. The AASHTO Red Book (AASHTO 2010), for example, publishes a dollar value of travel time, vehicle operating cost, and accidents based on multiple large surveys and databases. These values are widely used and therefore constitute a potential standard.

Given the easy availability and widespread acceptance of standard resources such as the AASHTO Red Book, and the inherent subjectivity of opinion data, it may be difficult to justify not using the standard resources and data-based methods. However, even if opinion is a necessary part of the equation, standardized methods can be used to make the alternatives more comparable, so the exercise of opinion is easier and more consistent. This is an important part of any cross-asset multi-objective tradeoff analysis.

3.4 ACCEPTABLE LEVELS OF SERVICE

Agencies frequently maintain estimates of preservation funding requirements necessary to sustain an acceptable level of service. These estimates typically are meant to include all asset classes and inflation over a long period of time, 10 years or more. The policy decision about what constitutes an acceptable network level of service should be consistent across asset classes, and is therefore a cross-asset decision.

Some of the draft TAM Plans developed to-date have provided a network-level investment analysis using FHWA’s proposed condition definitions of percent Good and percent Poor for pavements and bridges. These are done separately by asset class, and FHWA does not claim that “Good” and “Poor” have equivalent meanings for pavements and bridges. The analysis serves a valuable purpose of linking long-term funding expectations with performance, even if it does not necessarily imply a tradeoff between pavement and bridge programs.

In the future, agencies will be able to extend their TAM Plans to perform a similar analysis for safety, travel time, reliability, congestion, freight movement, and air quality because of recent rule-making proposals (FHWA 2016). In most of these cases the proposed rules have defined a “normal” or “desired” performance level in terms of measurable quantities, particularly travel time. It is not known yet how agencies will react to the proposals. There may be an implied equivalence between these criteria and acceptable/unacceptable, in which case each agency will need to evaluate whether the new performance measures communicate the desired message and whether they are a useful internal tool to track agency performance. As Table 3 shows, most agencies have access to more detailed data items that drive internal decision-making and define more precisely what they consider acceptable.

One way to establish cross-asset equivalence in level of service standards is to use a project-level scoping process as described below, on a sample of representative projects involving all asset classes of interest. This will provide typical values of performance measures and a set of relative weights for performance criteria including long term cost. A parametric analysis would investigate ten-year condition and performance outcomes for a range of realistic and above-realistic funding levels. If the percent of the inventory in unacceptable condition varies substantially by asset class, the researcher can then investigate whether the differences require adjustment in the level of service standards, or whether they merely reflect past imbalances in investment levels.

Another approach is to poll a random sample of customers to ask what levels of performance they consider acceptable or unacceptable. The responses can be analyzed using the Analytic Hierarchy Process (Maggiore et al 2015) or more simply by finding the median from a set of responses (Patidar et al 2007). This would rely on their intuitive sense of the meaning of "acceptable," which is complementary to the economic sense of equivalence in marginal returns.

3.5 NEEDS IDENTIFICATION

Many agencies maintain a listing and cost estimate of current capital needs, which may include replacement/reconstruction, preservation, functional improvements, risk mitigation, and new construction. Sometimes there is a list of selected categories of maintenance needs as well. There is often inconsistency within and across agencies in terms of how needs are defined, and what costs are included. Some examples of methods include:

- Polling agency officials asking them to create a list of needed work from memory or paper records;
- Systematic analysis in a pavement or bridge management system, to compute net benefits (in dollars) or a benefit cost ratio for potential treatments applied to each asset, selecting all those with positive net benefits.
- Application of level of service standards, minimum tolerable conditions, or action warrants to each asset to determine whether specific actions should be considered.

Often pavement and bridge management systems begin with condition standards and then apply a net benefit calculation to reduce the size of the needs list by eliminating investments with negative net benefits. In general, however, current practice is that needs are estimated without reference to fiscal constraints, and have a total cost significantly larger than likely funding levels. When needs estimates are computed using a benefit calculation, it is highly desirable to define benefits and costs in the same way across asset classes. This helps decision makers to understand and use the needs list in decision making. The programmatic cost estimates used in a needs estimate typically include all agency costs which are contingent on a decision to implement a project. They should include an overhead rate to account for mobilization, traffic control, land acquisition, demolition, engineering, and any other related costs that make funds unavailable for alternative uses.

The benefits used in a preservation needs calculation typically focus on long term cost. A typical model will consider the cost of an immediate project, and then estimate the timing and cost of subsequent treatments over a long time frame, often 50-200 years. This life cycle activity profile (Hawk 2003) is compared with a base-case or null alternative involving no action during the program time horizon (typically 10 years or more), or in some cases no action until a replacement action is warranted. The project is accepted into the needs list if its long term cost is lower than the null alternative long term cost. Many asset management systems also include user costs in this calculation, as discussed later in this report. Although these calculations are performed in an asset-specific way using asset-specific condition data and deterioration models within the individual asset management systems, the definition of cost and benefit should be consistent across asset classes so a consistent list of needs and a meaningful estimate of total needs can be produced.

Although the most common examples of this kind of long term cost analysis occur in pavement and bridge management systems, the same or similar methods are appropriate for many other asset classes. NCHRP Report 713 (Thompson et al 2012) explores various ways of creating these models. Some of the states have included, in their TAM Plans, network level long term cost models developed as spreadsheets for a variety of asset classes including pavements, bridges, culverts, ITS assets, unstable slopes and embankments, and retaining walls. In many cases these agencies do not yet have operational pavement or bridge management systems that can compute long term costs, but are still able to prepare network-level estimates in order to estimate preservation return-on-investment. This is often intended as an interim step to help build internal support for full implementation of management systems.

Even if a benefit calculation is not performed, consistency across asset classes can be achieved if level of service standards are developed with reference to a methodology to determine cost-effectiveness in an asset-generic manner. In current practice, level of service standards are often developed using judgment, and the developer may attempt to use a consistent concept of cost-effectiveness or may refer to industry research that finds certain treatments to be cost-effective under certain conditions, although the “cost effectiveness” criterion is not always well defined or consistent. Agencies may use a research project to perform benefit/cost analysis on a sample of assets to determine the range of conditions that make a given treatment cost-effective. This would give the agency more control over the assumptions used, to help ensure consistent definitions.

In the Pontis bridge management system, bridges are divided into structural elements, and each element is divided into condition states. Condition states have precise definitions that directly correspond to feasible treatments. When more than one treatment is feasible, a life cycle cost model selects the treatment that typically gives the lowest life cycle cost. On a given bridge, the elements and conditions found on the bridge are assigned to the optimal treatments, and the costs of all treatments are summed to yield total needs on the bridge. Agencies that are implementing geotechnical asset management programs, such as Alaska, Colorado, and Montana, use a similar approach based on condition states to provide a highly consistent definition of needs.

In a benefit calculation it is important to avoid double-counting of benefits related to condition. This is typically done in pavement and bridge management systems by using agency long term costs to represent the benefits of improving condition, and using user long term costs to represent all other performance benefits including safety and mobility.

Most cross-asset needs estimates found in state DOTs were developed entirely from current observed conditions. A pitfall of this limitation is that decision makers may be tempted to assume that the needs are to be implemented over a multi-year timeframe, which in turn may lead to deferring some needs into future, since their cost typically exceeds available funding substantially. This leads to incorrect conclusions and unrealistic expectations, because over a multi-year timeframe new needs will arise from deterioration and demand growth. Needs that cannot be met right away will increase in cost over time.

It is extremely important to communicate the timeframe of a needs estimate. If it is a multi-year estimate, it is critical that the effects of deterioration and demand growth be included. The use of performance forecasting models can help incorporating these effects in the assessment of future needs over a multi-year timeframe. The cost of future needs depends on the amount of deterioration and growth, which in turn depends on fiscal constraints. As a result, meaningful calculation of a multi-year needs estimate, even if presented as fiscally unconstrained, must include a fiscal scenario governing the rate of generation of new or expanded needs.

3.6 PROJECT LEVEL SCOPING

The analysis of cost-effectiveness on a given asset, used for needs identification, can also be used in making scoping decisions. The definitions of costs and benefits are the same for both applications, but for treatment selection typically multiple alternatives are evaluated and more than one might be found cost effective in terms of the differences in asset life-cycle costs and user benefits between alternatives.

In treatment selection, initially the alternative with the highest net benefit is selected. However, it is possible, because of funding constraints or project inter-relationships, that a lower-cost treatment might be a better choice, especially if its benefit is not much lower. Many pavement and bridge management systems can evaluate this possibility using an automated procedure. However, since the determination is based on asset-generic benefit and cost estimates, it can be made separately from asset-specific management systems. This is desirable if the tradeoff analysis is performed using the asset-generic Investment Candidate File.

It is common for agencies to formulate projects by combining needs across multiple assets, which may be in close proximity to each other or may share other implementation concerns. Very often the reason for combining the needs is to save money by taking advantage of a joint traffic control strategy or economies of scale. Commonly the combined project is prioritized as a unit. As is the case with individual assets, a multi-asset project may have multiple cost-effective scoping alternatives.

The cost of a multi-asset project is typically estimated by adding the separate direct costs of the individual assets, and then adding an indirect cost estimate computed based on the combined project. Project benefits are typically the sum of benefits computed for the individual assets in the project. Needless to say, the additivity of benefits is valid only if benefits are defined in the same way across all of the assets participating in the project. In pavement and bridge management systems, benefits include savings in agency long term costs, and avoided user costs related to functional deficiencies or risk. Benefits may be reported in terms of direct measures such as travel time and predicted accident count, but a combined measure for benefit/cost analysis and computation of net benefit would need to be performed in dollars.

Frequently agencies have policies of not revisiting a site more than once in a given period (such as 10 years). The scoping analysis can help ensure that any project considered has sufficient longevity and covers all likely needs. This is one reason why it is useful for the base case alternative, used in computing benefit, to involve a delay at least as long as the agency's minimum project interval. This may have the effect of increasing the amount of preservation work done on assets that are in relatively good condition, or it may result in delaying the project to allow time for more needs to arise, especially if indirect costs are significant.

3.7 PRIORITY PROGRAMMING AND RESOURCE ALLOCATION

When funding is constrained, the agency typically will not have enough money to implement all its current needs, so some will need to be delayed. In a cross-asset priority-setting process, it is necessary to find a consistent way to prioritize work candidates so the total benefit achieved from each year's investments is maximized. Since different asset classes affect different performance objectives in different ways, a cross-asset priority criterion is also multi-objective.

As is the case with the long-term funding and policy analysis, multiple objectives can be combined using a weighting scheme (Patidar et al 2007). The existence of a budget constraint imposes some additional requirements:

- Selecting a project means removing the cost of the project from availability for any other needs anywhere in the network. So the opportunity cost is a network level effect. Benefits must be treated in the same way. All of the project's benefits to the network must be considered, including the performance benefits or avoided user costs enjoyed by every road user affected by the project.
- Consistent with the discussion of diminishing marginal returns above, each dollar added to the program should be selected from the project that can give the highest benefit for that dollar. Since projects are prioritized as a unit, this means that each investment added to the priority list should be the one that gives the highest ratio of increase in benefit to increase in cost, or incremental benefit/cost ratio.
- In most applications there is a separate budget constraint for each year of a multi-year program. In the benefit calculation, the default or null alternative is to take no action in the year being analyzed, but instead recognize a one-year delay (accounting for further deterioration and traffic growth) and consider the project again in the following year. This is different from the convention typically used for a cost-effectiveness determination, where action may be postponed for many years in the null alternative.

If stakeholder concerns overlap, there is potential for double-counting of benefits, which must be avoided. One approach is to use models of the cause-and-effect relationship between condition and the other performance concerns. The effects of condition are then expressed through changes in the performance measures experienced by stakeholders. For example, pavement roughness is expressed through increase in vehicle operating costs (Chatti and Zaabar, 2012); advanced bridge deterioration is expressed through reduced operating rating and truck detours; and traffic control device failure is expressed through higher crash risk. If some aspect of condition is not fully represented in this way, the condition measure is narrowed to a carefully-circumscribed definition that avoids double-counting the other performance benefits. In fact, if the analysis fully considers long term cost, safety, mobility, and environmental sustainability, it may be acceptable to omit condition entirely from the priority criterion, since the effects of condition might already be fully represented by the remaining criteria.

The weighting scheme for combining of multiple performance criteria is usually additive in most TAM applications, but can be multiplicative or take other forms in advanced applications (Patidar et al 2007). The additive form is simplest and that is why it is most commonly used. The weights applied to the performance criteria can take several forms. Two general patterns are commonly observed:

- **Utility theory** (Patidar et al 2007): Each performance criterion is transformed into a unitless quantity, and then the transformed criteria are summed. This pattern is typically seen if none of the performance criteria are economic in nature, or if some of the criteria are purely judgment-based.
- **Social cost** (AASHTO 2010): Each performance criterion is transformed into an equivalent dollar value, using research-based metrics. The dollar values are summed.

If any of the stakeholder objectives are expressed in dollar terms (particularly long term cost), the utility approach and social cost approach are functionally equivalent, since the relative weight of the economic criterion implicitly assigns unit dollar values to the non-economic criteria. When a TAM analysis addresses all of the business functions described in this chapter, social cost is usually the simplest and most intuitive way to express benefits.

3.8 PERFORMANCE TARGETING AND TRACKING

If the agency has an Investment Candidate File in place and has computed costs and benefits as discussed in the previous sections, it has all the ingredients it needs to extend the priority-setting function to resource allocation and target setting. Each project in the investment candidate file is tagged with identification information related to the various ways resource allocations or performance forecasts might be needed. Project costs and performance outcomes are summed for each tag to provide the resulting network level costs and outcomes.

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CHAPTER 4. DATA AND ANALYSIS RESOURCES

All of the useful performance measures for TAM tradeoff analysis ultimately rely on measurable data. Various calculations are performed to forecast future values of the data in a manner that is sensitive to agency actions; to summarize highly technical data into a form that more directly reflects agency objectives and needs; to combine dissimilar quantities and objectives; to create metrics that have consistent meaning across asset classes; and to facilitate clear communication.

4.1 CONDITION

State transportation agencies all gather condition data for pavements and bridges, and most also maintain condition surveys for additional asset classes. Pavement condition data has become highly automated in recent years, but most other data are gathered visually. Table **4** summarizes the data commonly available.

Table 4. Condition data and corresponding performance objectives.

		Performance concerns			
Property	Method	Long term cost	Safety	Mobility	Environment
Pavements					
Roughness (IRI)	Automated	x	x	x	
Rutting	Automated	x	x	x	
Cracking	Automated	x			
Faulting	Automated	x	x	x	
Frost heave	Visual or automated	x	x	x	
Surface distress	Automated	x			
Bearing capacity	Automated	x			
Skid	Automated		x		
Noise	Automated or reported				x
Structures (bridges, culverts, tunnels, sign and light structures, retaining walls, buildings)					
Element condition states	Visual	x			
NBI conditions	Visual	x	x	x	
Scour rating	Visual	x		x	x
Fatigue	Visual	x	x	x	x
Unstable slopes (rock, soil, embankments)					
Condition states	Visual	x	x	x	x
Rockfall hazard score	Visual	x			
Traffic control devices (signs, signals, markings)					
Operational (Y/N)	Visual		x	x	
Retroreflectivity	Visual or automated		x		
Legibility	Visual		x		
Guardrail					
Damage	Visual		x		
Lighting					
Operational (Y/N)	Visual		x		
Sidewalks, bike trails					
Unevenness	Visual		x	x	

Industry standards exist for many of these data collection processes. For example, FHWA's 2015 Notice of Proposed Rule-Making, in 23 CFR 490.111, incorporates ten AASHTO standards documents governing pavement data collection, as well as the HPMS Field Manual (FHWA 2014). Visual inspection of bridges is governed by the National Bridge Inventory Coding Guide (FHWA 1995) and by the AASHTO Manual for Bridge Element Inspection (AASHTO 2013).

4.1.1 CONDITION STATES

AASHTO's bridge element inspection process has frequently been used as a model for visual inspection of other transportation assets. For example, Colorado DOT developed a similar manual to cover overhead sign structures, traffic signals, and high-mast light poles (LONCO 2007). Alaska DOT developed a similar specification for rock and soil slopes, and retaining walls (Beckstrand et al 2016). Under MAP-21 requirements in 23 USC 144(d)(2), FHWA is proposing to make a portion of the AASHTO manual mandatory as a part of the National Bridge Inventory.

Table **5** shows the mandatory elements.

The AASHTO manual provides four condition states per element for increasing levels of severity of each of the following defects: delaminations, spalls, and patched areas; exposed rebar or prestressing tendons; efflorescence and rust staining; corrosion; cracking, load capacity, collision damage; damaged connections; timber decay; timber checks; abrasion; distortion; settlement; scour; mortar breakdown; masonry displacement; restricted movement or misalignment of bearings; bulging, splitting, or tearing of elastomeric bearings; loss of bearing area; debris impaction; and damage to expansion joint hardware or deck interface. All of these defects are to be considered by the bridge inspector when assigning an element condition state, but the manual only calls for recording the defect having the most significant effect. As an example, Table **6** shows the defect descriptions that go into the assessment of the condition states of a reinforced concrete deck.

Typically condition states are defined in a manner that reflects the feasibility of potential treatments. Condition state 1 requires no treatment, state 4 requires replacement, and states 2 and 3 imply some level of preservation or risk mitigation. This linkage with treatment feasibility helps to ensure that condition states are defined in a consistent way across elements and asset classes.

Table 5. National Bridge Inventory (NBI) Elements in the AASHTO Manual for Bridge Element Inspection (AASHTO 2013, FHWA 2014).

Deck elements	
12	Re Concrete Deck
13	Pre Concrete Deck
15	Pre Concrete Top Flange
16	Re Conc Top Flange
28	Steel Deck - Open Grid
29	Steel Deck - Conc Fill Grid
30	Steel Deck - Orthotropic
31	Timber Deck
38	Re Concrete Slab
54	Timber Slab
60	Other Deck
65	Other Slab

Superstructure elements	
102	Steel Clsd Box Gird
104	Pre Clsd Box Girder
105	Re Clsd Box Girder
106	Othr Clsd Web/Box Girder
107	Steel Opn Girder/Beam
109	Pre Opn Conc Girder/Beam
110	Re Conc Opn Girder/Beam
111	Timber Open Girder
112	Other Open Girder/Beam
113	Steel Stringer
115	Pre Conc Stringer
116	Re Conc Stringer
117	Timber Stringer
118	Other Stringer
120	Steel Truss
135	Timber Truss
136	Other Truss
141	Stl Arch
142	Other Arch
143	Pre Conc Arch
144	Re Conc Arch
145	Masonry Arch
146	Timber Arch
147	Stl Main Cables

Superstructure (continued)	
148	Sec Steel Cables
149	Otr Secondary Cable
152	Steel Floor Beam
154	Prestress Floor Beam
155	Re Conc Floor Beam
156	Timber Floor Beam
157	Other Floor Beam
161	Stl Pin Pin/Han both
162	Stl Gus Plate

Substructure elements	
202	Steel Column
203	Other Column
204	Pre Conc Column
205	Re Conc Column
206	Timber Column
207	Stl Tower
208	Timber Trestle
210	Re Conc Pier Wall
211	Other Pier Wall
212	Timber Pier Wall
213	Masonry Pier Wall
215	Re Conc Abutment
216	Timber Abutment
217	Masonry Abutment
218	Other Abutments
219	Stl Abutment
220	Re Conc Sub Pile Cap/Ftg
225	Steel Pile
226	Pre Conc Pile
227	Re Conc Pile
228	Timber Pile
229	Other Pile
231	Steel Pier Cap
233	Pre Conc Pier Cap
234	Re Conc Pier Cap
235	Timber Pier Cap
236	Other Pier Cap

Culverts	
240	Steel Culvert
241	Re Conc Culvert
242	Timber Culvert
243	Other Culvert
244	Masonry Culvert
245	Pre Concrete Culvert

Joints	
300	Strip seal joint
301	Pourable joint
302	Compression joint
303	Assembly joint with seal
304	Open joint
305	Assembly joint without seal
306	Other joint

Bearings	
310	Elastomeric Bearing
311	Moveable Bearing
312	Enclosed Bearing
313	Fixed Bearing
314	Pot Bearing
315	Disk Bearing
316	Other Bearing

Railings	
330	Metal Bridge Railing
331	Re Conc Bridge Railing
332	Timb Bridge Railing
333	Other Bridge Railing
334	Masry Bdge Rling

Protective systems	
510	Wearing surfaces
515	Steel protective coating
521	Concrete protective coating

Table 6. Definition of condition states – Element 12, Reinforced concrete deck (reproduced from AASHTO 2013).

Defects	Condition States			
	1	2	3	4
	Good	Fair	Poor	Severe
Delamination/Spall/ Patched Area (1080)	None	Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.	Spall greater than 1 in. deep or greater than 6 in. diameter. Patched area that is unsound or showing distress. Does not warrant structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Exposed Rebar (1090)	None	Present without measurable section loss.	Present with measurable section loss, but does not warrant structural review.	
Efflorescence/Rust Staining (1120)	None	None Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Cracking (RC and Other) (1130)	Width less than 0.012 in. or spacing greater than 3.0 ft.	Width 0.012-0.05 in. or spacing of 1.0-3.0 ft.	Width greater than 0.05 in. or spacing less than 1.0 ft	
Abrasion/Wear(PSC/RC)(1190)	No abrasion or wearing	Abrasion or wearing has exposed coarse aggregate but the aggregate remains secure in the concrete.	Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear.	
Damage (7000)	Not applicable	The element has impact damage. The specific damage caused by the impact has been captured in condition state 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in condition state 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in condition state 4 under the appropriate material defect entry.

4.1.2 CONDITION INDEXES

Condition data can be quite detailed, so it is useful to define a condition index which summarizes the condition of a specific asset consistent with the stated performance goal (e.g. user LOS, life-cycle cost, safety). This can be used to compare two or more assets of the same class, or to track condition over time. For preservation of pavement assets, there is an ASTM standard for computing the Pavement Condition Index (ASTM 2016). The method assesses and combines ratings for 19 distress types. The severity and extent of these distresses is rated and scored using a system of deduct points. The result is a Pavement Condition Index (PCI), ranging from 100 for a perfect, new pavement to 0 for a completely failed pavement. Various adaptations of this method (usually with fewer distresses) have been implemented by most states and most pavement management systems.

Pavement condition surveys do not usually incorporate condition states in the manner done with bridges. However, a similar function is provided in pavement management systems by discretizing ranges of PCI or of individual distresses, to establish the feasibility of actions. In some systems treatment feasibility is determined using decision trees to codify business rules for action selection.

In a similar manner, Caltrans developed a Bridge Health Index as a weighted average score combining all the elements and condition states on a bridge (Shepard and Johnson 2001). This has been incorporated into AASHTO bridge management software systems and implemented by most of the states. Similar methods can be used for any asset class where visual condition state data are available.

4.1.3 PERFORMANCE IMPACTS

As suggested in Table **4** above, condition data can be incorporated into calculations of any type of performance impact. Some common models for these calculations are discussed in the following sections. As products of active research areas, these models are not standardized in the same way that condition data are standardized. However, many of these models can be found in federally-supported analysis systems such as HERS (FHWA 2005) and NBIAS (Cambridge 2011) as well as in state-supported asset management systems.

4.2 RESILIENCE AND RISK

Transportation agencies are increasingly concerned with transportation network resilience (Committees 2012, Hughes 2014), and asset management can help to maximize this characteristic by improving the resilience of individual assets. Resilience is defined as:

> *… the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must* (Allenby and Fink 2005).
> *'Vulnerability' seems largely to imply an inability to cope and 'resilience' seems to broadly imply an ability to cope. They may be viewed as two ends of a spectrum (Levina and Tirpak 2006).*

"Internal and external change" can be interpreted as changes caused within the asset itself (i.e. normal deterioration) and change caused by external forces (natural extreme events, such as floods and earthquakes). “Maintain its functions and structure” can be interpreted as the avoidance of transportation service disruptions.

Resilience is a useful concept as a way to collect and summarize the properties of an asset that contribute to risk. There can be a significant number of hazards and properties. For example, NCHRP Project 20-07(378) is currently developing a risk assessment guideline for bridge management systems, which considers 16 hazards: earthquake, landslide, storm surge, high winds, floods, scour, wildfire, extreme temperature, permafrost instability, overloads, over-height collisions, fuel tanker truck collisions, vessel collisions, terrorism, advanced deterioration, and fatigue (unpublished work in progress). For each of these hazards, the project is documenting the variables affecting risk, methods to estimate the likelihood of service disruptions, and methods to estimate the consequences of service disruptions.

Appropriate research could develop similar models for other asset classes. In Alaska’s geotechnical asset management process, the factors affecting resilience – such as slope geometry, geological characteristics, condition, and mitigation effectiveness – are summarized in the form of three resilience states, defined as follows (Thompson 2016):

> Good: The asset is fully sufficient to resist anticipated hazards and normal deterioration according to current standards.
>
> Fair: The asset is sub-standard, and as a result there is elevated likelihood of mild-to-moderate disruption to mobility, safety, economic efficiency, or other performance objectives on the corridor. Risk mitigation may reduce this likelihood.
>
> Poor: The asset is ineffective in resisting anticipated hazards, and as a result there is high likelihood of severe disruption to corridor performance objectives. Significant investment such as reconstruction may be needed.

Each of these is then associated with a likelihood of service disruption, expressed as a probability. The consequences of service disruption are calculated in the form of long term agency cost (cost of incident recovery), safety (excess accident risk), and mobility (travel time and vehicle operating cost associated with detours and delays).

4.3 AGENCY COST

Agency cost plays multiple roles in TAM tradeoff analysis. Since all of these roles often occur prior to design of a project, they tend to be rough estimates based on historical experience with similar types of work. Using the business process and applications introduced in Chapter 3, the roles are:

- Needs identification – A cost estimate is used in the denominator of a benefit/cost ratio, to support a determination of whether a given treatment is cost-effective for a given asset, and to compare two or more alternative treatments. The estimate might be prepared for the specific asset where work is contemplated, or might be developed for a more generic set of assets similar to the one being considered.

- Project scoping – When multiple treatments and/or multiple assets are combined into a project, each asset contributes a direct cost, computed in an asset-specific way, that is proportional to the quantity of work required, where quantity is estimated based on output or resource estimates. The project overall is then analyzed for asset-generic indirect costs, where economies of scale or shared traffic control strategies may occur. Indirect costs include mobilization, work zone traffic control, engineering, land acquisition, environmental protection, demolition, and contingencies. The cost estimate in project scoping may differ from needs identification, where assets are not usually combined into projects, and where indirect costs are quantified only as a general overhead factor.
- Priority programming and resource allocation – For this application the initial cost of a project should be treated as an opportunity cost – the amount of money in the budget that becomes unavailable for any other agency use. Therefore the scope of the cost estimate must agree with the scope of the budget estimate used in priority setting and resource allocation. This scope can vary among agencies depending on how they implement and account for certain project delivery functions such as design and maintenance of traffic. Once a project enters the environmental review or design stage, its scope may change and its cost estimate may become more precise.
- Long-term cost – The inter-temporal tradeoff between near-term preservation and longer-term rehabilitation or replacement is quantified by creating a forecast of future costs likely to occur on the subject assets in order to keep them in service. The timing and scope of such future work depends on the near-term decisions about scope and timing of the project. In typical long term cost analyses, future conditions and performance are forecast using deterioration and traffic growth models, and then decision rules determine the scope and timing of future projects. Cost estimates for the future work are developed at the same level of detail as for needs identification. Methods used for deterioration modeling and future cost estimation are asset-specific.

Agencies determine cost-effectiveness and benefit/cost ratio by making pair-wise comparisons between project alternatives. Each candidate investment is compared with a base case in which no work is performed during the program period (for needs identification and project scoping), or a base case in which the decision is postponed for one year (for priority programming).

Pavement and bridge management systems in use today do not all have the capabilities described here for the various types of cost analysis. Most are able to perform a long term cost calculation, but very few are able to combine assets into projects for estimation of indirect costs. AASHTO is developing a bridge management system (AASHTOWare Bridge Management release 5.2.3) which is expected to have these capabilities within the structures asset class, but not across other asset classes.

4.3.1 DEVELOPING COST ESTIMATES

Every transportation agency has a need for programmatic cost estimates for the STIP and for initiation of the project design process. A few agencies devote databases and staffing positions to the process of gathering project cost data, developing cost estimation metrics, developing engineer’s estimates, and checking contractor bids. Other agencies focus relatively little attention to this function and may be reluctant to rely on the data they have. Cost estimation in those cases may be very informal and not easily automated.

NCHRP Report 668 (Hearn et al 2010) developed a framework for overcoming some of the data quality problems that agencies have in developing programmatic cost estimates. The process requires that the agency have a database of the relevant assets and a history of condition information. It must also have a database of past projects, which identify the assets receiving work, some sort of description or classification of the work, a completion date, and a cost. The framework and software were developed primarily for bridges, where few agencies have a work classification scheme that is anywhere near as detailed as the classification scheme built into bridge management systems.

The process relies on a multi-level classification of maintenance activities: first by component (deck, superstructure, substructure, joints, bearings, etc.), then by operation (clean, coat, repair, modify, replace, etc.), then by activity, which is a more detailed taxonomy within each operation. The actions defined within the bridge management system are matched up with this classification scheme.

The project database and bridge inspection database are merged using the bridge identifier and date, sub-dividing multi-bridge projects as needed. Each bridge project is associated with the inspection that occurred just before and just after the work, including element inspections. Elements that improved in condition, and the affected condition states, provide a clue as to the specific kinds of work that were done. Each project is matched to the multi-level classification scheme according to any information available either on the project record or the improved element conditions. This process may be partly automated and partly manual. For projects involving multiple bridges and/or elements, costs are allocated according to the quantities improved.

For each element and activity, the unit cost is the total expenditure divided by the total quantity, possibly adjusted for inflation and scaled to represent control totals for total costs and for indirect costs such as traffic control that might not be included in the project database. Considerable judgment is required to review the unit costs for reasonableness.

In some cases, especially work done by internal forces, agencies do not have project cost data but do have resource data. The analyst must first produce a resource-based cost estimate based on typical resource costs and overhead, before embarking on the rest of the process.

Florida DOT used a very similar process in preparing its Pontis cost models (Sobanjo and Thompson 2001). This analysis is currently being updated and will be published later in 2016. Table **7** shows the activity classification scheme that is being used. It is straight-forward to imagine how this methodology can readily be applied to any other asset class having suitable data.

Table 7. Activity classification for developing unit costs (Florida DOT unpublished work in progress).

			Action Category		
		Object	100-Replace	200-Major repair	300-Minor repair
Materials	1	Deck	101	201	301
	2	Steel/metal		202	302
	3	Concrete		203	303
	4	Timber		204	304
	5	Masonry		205	305
	6	MSE		206	306
	7	Other material		207	307
	9	Wearing surface	109	209	309
Hi-Maint	10	Other element			
	11	Joint	111	211	311
	12	Joint seal	112		
	13	Bearing (incl p/h)	113	213	313
	14	Railing	114		
	19	Coatings	119	219	319
Drainage	21	Slope prot	121	221	
	22	Channel		222	322
	23	Drain sys	123	223	323
Machinery	31	Machinery (1)	131	231	331
	32	Cath prot	132	232	332
Major	41	Beam	141		
	42	Truss/arch/box	142		
	43	Cable	143	243	
	44	Substr elem (exc cap)	144 (2)		
	45	Culvert	145		
	46	Appr slab	146	246 (3)	
	47	Settlement/scour		247 (4)	
	48	Distortion		248 (5)	
Appurtenances	51	Pole/sign	151		

White cells represent valid sub-categories; numbers in parentheses refer to footnotes

Footnotes

1. Incl. elec, hydraulic, and mech elements
2. Incl. fenders, dolphins, and pile jackets
3. Mudjacking
4. Mitigate settlement or scour
5. Heat straightening and repair of distortion

4.3.2 LONG TERM COST

Over the course of its life, each asset undergoes deterioration because of age, traffic, weather, water and earth movement, freeze/thaw, and other factors. The effect of deterioration is to increase the likelihood of service disruptions, and to increase the frequency and cost of routine, reactive maintenance such as pothole filling and sealing of cracks. Occasionally it is necessary for the agency to intervene with preservation action to counteract this deterioration.

Preservation and risk mitigation treatments have important inter-temporal tradeoffs. In many cases a small timely investment in preservation can extend the life of an asset and postpone the day when a major reconstruction might be necessary. If such a treatment is feasible but is not accomplished in a timely way, further deterioration may render it infeasible or increase the rehabilitation cost substantially. Life cycle cost analysis informs these tradeoffs (FHWA 2002, Hawk 2003).

In life cycle cost analysis, all of these costs are expressed in dollars and combined in a framework where tradeoffs in scope and timing of work can be evaluated. Figure **11** shows the ingredients:

- A treatment model (green) forecasts the costs and effects of mitigation and preservation activities in each condition or resilience state. The amount of each treatment is guided by a treatment policy and constrained by available funding.
- A deterioration model (yellow) forecasts the change in condition from year to year when no treatment is applied, starting with current conditions from the most recent inspection.

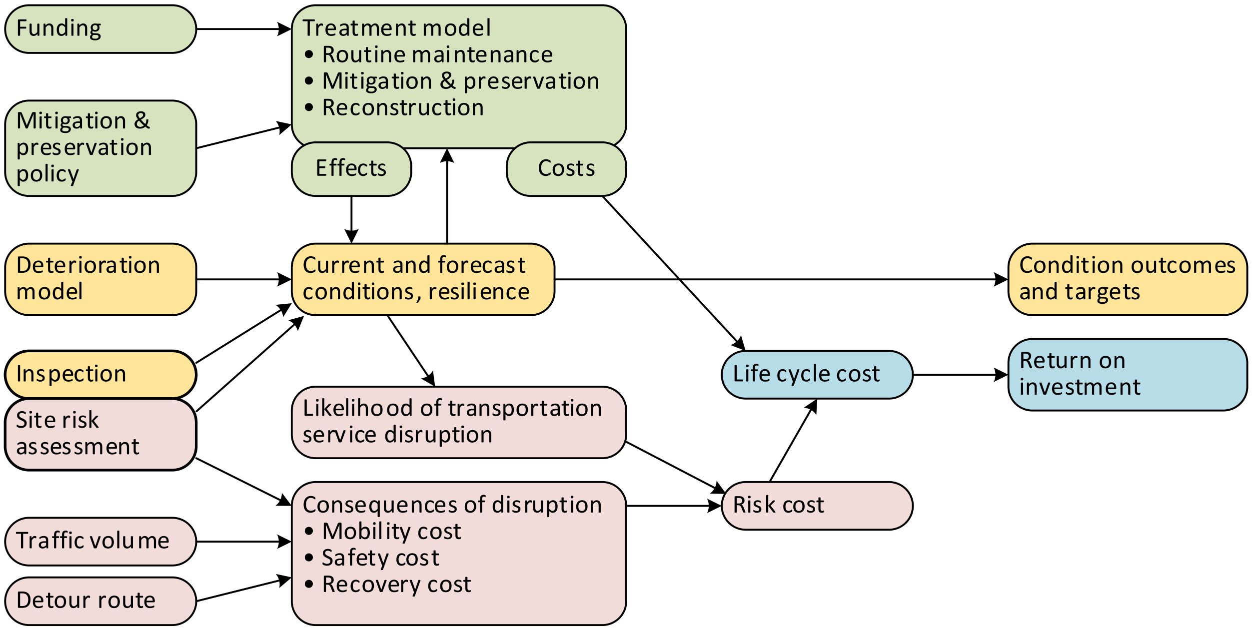

Figure 11. Analytical framework surrounding life cycle cost analysis.

- The risk model (red) uses a site assessment of potential safety, mobility, and environmental impacts, along with data on traffic and detour routes. The resilience of each asset affects the likelihood of service disruptions, thus affecting the expected value of disruption costs.
- Agency and user costs are combined into life cycle cost. All costs are discounted, based on the year in which the costs are incurred, to reflect the time value of money. By comparing different policy and funding alternatives, the agency can compute economic metrics such as long term social cost savings and return on investment.

User costs associated with risk and functional deficiencies are discussed later in this chapter. In decisions regarding needs identification and project scoping, it is valuable to incorporate these user costs directly into long term costs in order to estimate long-term benefits, which have uncertainty and can be discounted in the same way as long-term agency costs. For priority programming, where only one year of benefits is at stake, it is common in pavement and bridge management systems to keep the user benefits separate from long term cost. This is because agency benefits are influenced by the potential of preservation to be made infeasible by a one-year delay, while the feasibility of risk mitigation and functional improvement usually is not affected by project delays.

The primary forecasting models (deterioration, treatment cost and effect, and disruption likelihood) are research-based. The best such models used in pavement and bridge management rely on many years of quality-assured data, which the agency might not yet have for other assets. The agency will need to start with what research and data can be found, some from other agencies, along with the best available expert judgment. In a bootstrapping process it will gradually use these initial models to build a sustainable TAM program while at the same time maintaining good records of the conditions observed, treatments accomplished, and adverse events, so it can improve its forecasting models.

Treatment model. A long term cost model forecasts condition each year and considers taking action based on the forecast conditions and resilience. A set of action criteria determines whether an action is generated. In bridge management systems these actions are generated at the element level, while models for other asset classes, including pavements, generate actions that apply to the entire asset. Each action has a unit cost and a procedure to estimate the resulting improvement in condition and resilience.

Deterioration. The simplest possible deterioration model using condition state data is a Markov model, which expresses deterioration rates as probabilities of transitions among the possible condition states each year. This type of model is used in nearly all bridge management systems, and in a few pavement management systems as well. It is also by far the most common choice for other asset classes such as culverts, slopes, and traffic control devices. A Markov model can be expressed as the vector of median transition times from each state to the next. The methods for developing and using these models are documented in NCHRP Report 713 (Thompson et al 2012). Table **8** shows the models that were developed for rock slopes, using the methods described below, for Alaska DOT (Beckstrand et al 2016).

Table 8. Markov deterioration model (rock slopes).

Deterioration model	Markov model - starting condition state				
	State 1	State 2	State 3	State 4	State 5
Transition time (years)	38.3	32.5	21.2	13.7	--
Same-state probability	0.9821	0.9789	0.9678	0.9507	1.0000
Next-state probability	0.0179	0.0211	0.0322	0.0493	0.0000

In this table the transition time is the number of years that it takes for 50% of a representative population of assets to deteriorate from each condition state to the next-worse one; for example, from state 1 to state 2. The same-state probability is the statistical probability, in any one year, that a given asset will remain in the same condition state one year later. The next-state probability is then the probability that a given asset will deteriorate to the next-worse condition state. In the models used here, the sum of the same-state probability and next-state probability is always 1.0000.

If the transition time is known or estimated, the same-state probability can be computed using the formula:

$$p_{jj} = 0.5^{\left(\frac{1}{t}\right)}$$

Where j is the condition state (before and after 1 year)
t is the transition time in years

For any given condition state, the fraction in that state after one year is computed by multiplying the current fraction in each state by the corresponding same-state and next-state probabilities. This calculation can be repeated as many times as needed in order to extend the forecast for additional years in the future.

If an agency does not yet have the asset condition history required in order to develop deterioration models using statistical methods, an expert judgment elicitation process is used instead. A panel of experts is asked a series of structured questions such as the following: "Suppose 100 rock slopes are currently in condition state 2. After how many years will 50 of the slopes reach state 3 or worse, if no action is taken?" Each panelist is asked to answer the questions independently from his or her own experience, then the results are tabulated and discussed. Panelists are then allowed to change their answers, which can help to improve the level of common understanding and consensus. For each question, the mean response is used as the transition time. Transition probabilities are then computed from this information as shown above.

Figure **12** shows the combined effect of the deterioration and treatment models, expressed as a condition index where 100 is a new asset and 0 is the worst possible condition. This example reconstructs the asset when the probability of condition state 5 reaches 50%, and has periodic mid-life corrective actions.

Time value of money. The key tradeoff in long term cost analysis is the ability to spend a small amount of money in the near future in order to postpone a much larger expenditure. Economists use a metric known as a discount rate to measure the benefit of postponing costs. If a 2% discount rate is used, for example, then the benefit of postponing a $1 million expenditure for one year is 2% of that amount, or $20,000. It would be worth spending up to $20,000 today in order to postpone that $1 million expenditure for one year.

If a large expense can be postponed long enough, it might become nearly insignificant in near-term decision making, because the delay in having to pay the expense is valuable in itself. In long term cost analysis, if a cost can be delayed its magnitude is reduced, or discounted, according to the discount rate and the length of the delay. The present value of a future cost, known as the discount factor, can be computed from the discount rate d and the number of years of delay t using:

$$DF = \left(\frac{1}{1+d}\right)^t$$

Figure 12. Deterioration, reconstruction, and preservation (rock slopes).

So if the discount rate is 2%, delaying a replacement expenditure of $1 million for 10 years reduces the value of that expenditure to $820,348 and delaying it for 100 years reduces it to $138,033. This is still a significant amount of money compared to preservation costs, and might not be enough of a reduction to render subsequent costs insignificant to present decision making. TAM Plans often extend the life cycle cost analysis to a reasonable asset-specific analysis period, such as 50 years for pavements and 200 years for rock slopes, to ensure that far-future costs are sufficiently discounted.

The discount rate is determined by agency policy, which should be consistent across all types of assets and all investments of similar lifespan. A common source of guidance is The White House Office of Management and Budget (OMB) Circular A-94 (OMB 2016). Typically inflation is omitted from long term cost analyses because this practice simplifies the computations. A riskless and inflationless cost of capital for long-lived investments may use 30-year US Treasury bonds for guidance, with a 2016 real interest rate of 1.5%. Transportation agencies usually specify higher discount rates than this, because of uncertainties in long-term future travel demand and infrastructure requirements. In recent (as of May 2016) TAM Plans, discount rates in the 1.9% to 2.4% range have been observed.

4.4 SAFETY

Safety-related performance is typically expressed in terms of the number of accidents, number of fatalities, or number of injuries. Recent federal rule-making in 23 CFR 490 Subpart B promulgates five measures (FHWA 2016):

- Number of fatalities
- Rate of fatalities per 100 million vehicle-miles traveled
- Number serious injuries
- Rate of serious injuries per 100 million vehicle-miles traveled
- Number of non-motorized fatalities and serious injuries

4.4.1 CRASH PROBABILITY

When safety objectives are considered within a risk-based asset management framework, the asset characteristics related to crash probability or crash rate can be included within the concept of resilience in Figure **5**, and can be computed in asset-specific tools. Crash risk methods for pavements would differ from methods used for bridges, unstable rock slopes, traffic signals, etc. The result of the calculation would be an estimate of probability which can be used further in asset-generic tradeoff analysis. Examples of significant variables include:

- Pavements:
    - Roughness
    - Potholes
    - Skid resistance

- Bridges:
    - Roadway width
    - Approach alignment
    - Deck condition
    - Functional class

- Rock slopes:
    - Slope condition
    - Geological character
    - Slope geometry
    - Water infiltration

- Traffic signals:
    - Mean/median time between failures
    - Legibility
    - Compliance with standards

- Guardrails:
    - Impact resistance
    - Compliance with standards

Existing research provides guidance to estimate many of these probabilities. For example, Florida DOT developed an accident risk model for bridges (Thompson et al 1999). This model, developed using a regression analysis of bridge characteristics and crash statistics, computes accident likelihood as follows:

Expected accidents per year = (Term1 + Term2 + Term3)/1000, where:

Term1 = 886.0098 for urban arterials (functional class 14 or 16), or -377.3701 otherwise
Term2 = 0.7323*lanes*length
Term3 = coef3*lanes/roadwidth*adt

Where "length" is the structure length in meters (NBI item 49) and "lanes" is the number of lanes (NBI item 28). For roadways under the bridge, "length" is the bridge deck width (NBI item 52) in meters. "Roadwidth" is the traveled way width in meters (NBI item 51) and "adt" is the average daily traffic forecast for the year being analyzed. The coefficient on term3 takes the following values based on approach alignment (NBI item 72) and deck condition (NBI item 58):

If approach <= "6" and deck <="6"	0.7899
If approach <= "6" and deck >"6"	0.5031
If approach > "6" and deck <="6"	0.4531
If approach > "6" and deck >"6"	0.3904

Note that this model was developed for metric data.

As is appropriate for all TAM applications, the crash estimate is developed to estimate the incremental effect on crashes of asset management decisions. Each road will have a variety of crash causes, most of which are unrelated to asset management. The crash probability model is meant to be used a benefit calculation where two alternatives are compared, and the difference between the two in terms of crash probability is the significant result of the calculation.

Traffic safety data at the roadway segment or bridge level are notoriously irregular, so the federal rules specify a five-year rolling average even at the statewide level. In a bridge management application such as Florida's the tradeoff analysis and performance management reports do not use actual crash rates at all, but instead use the crash probability model as a proxy based on bridge characteristics. Risk mitigation actions such as widening or realignment cause changes to the crash probability model inputs, thus reducing the predicted number of accidents.

Actual and forecast number of crashes per year is a useful measure of safety for network-level applications such as priority-setting and resource allocation, since the contributions of individual assets can be summed to estimate a network-wide performance measure. For comparisons among individual assets or groups of assets, for level of service standards, and for tracking of performance over time, it is more useful to normalize the number of crashes by dividing by traffic volume or vehicle-miles traveled. This removes the effects of utilization, which can be highly variable among assets, and places diverse assets on a common and meaningful scale.

4.4.2. MONETIZING SAFETY BENEFITS

AASHTO's Red Book (AASHTO 2010) provides economic measures that can fit any of these safety measures, enabling the estimation of social cost. The most comprehensive definition used in the Red Book is the number of motor vehicle accidents, which includes property-damage-only (PDO) crashes not addressed in any of the Federal measures. Pavement and bridge management systems typically include PDO crashes in their project benefit estimates if they consider user costs. However, they do not typically consider non-motorized fatalities or injuries.

The Red Book has procedures and research-based metrics which take into account typical crash injury severity rates and property damage. For most applications of asset risk analysis, it is appropriate to use the figures on Red Book page 5-24, using the average over all vehicle classes and accident types. This excludes insurance reimbursement to avoid double-counting of costs.

The calculation is 3.394 vehicle accidents per million VMT, divided by \$0.1062 per VMT. Updated to 2016 dollars using the Consumer Price Index (BLS 2016), this figure is \$43,694 per vehicle per crash. The safety consequence for a single- crash is then:

$$CQ \quad = 43{,}694 \times VC$$

VC = count of vehicles involved in the crash

The hazard scenario would determine the number of vehicles involved in a crash. In most asset management scenarios this would be just one. The Red Book does not provide guidance on multi-vehicle crashes, but mining of agency crash records might suggest a larger number for certain scenarios. For a worst-case scenario where a structure collapses while in service, the vehicle count can be estimated from:

$$VC \quad = \frac{ADT}{24} \times \frac{1}{speed} \times \frac{length}{5280}$$

Where $length$ is the bridge length for roadways on the bridge, and bridge width for roadways under a bridge. If the likelihood of a crash depends on traffic volume (over-height truck collisions, for example), the speed and traffic volume should reflect a busy time of day. If the likelihood does not depend on traffic volume (e.g. earthquakes), then a daily average of speed and volume should be used. Speed may be obtained from HPMS data.

When forecasting future crash consequences, traffic growth should be taken into account, using appropriate forecast growth rates based on transportation plans.

For many hazards, mitigation effectiveness is an important determinant of adverse event consequences. For example, seismic restraining devices and column wraps are meant to reduce the bridge safety consequences of earthquakes. Rockfall fences and barriers reduce the potential safety consequences of rockfall events. Geotechnical asset inspection procedures such as those used in Alaska (Beckstrand et al 2016) explicitly require the inspector to classify the effectiveness of any mitigation elements found to be present. This causes a proportional reduction in rockfall event consequence costs.

Certain types of projects may reduce the economic consequences by reducing the probability of fatalities. This is especially the case for guardrail or bridge rail improvements. The AASHTO Red Book provides fatality and injury crash costs separately so the cost factor can be adjusted to reflect the effectiveness of these projects.

4.5 MOBILITY

Mobility has several dimensions that can be affected in different ways by different assets. It can refer to motorized traffic in general, to freight or other market segments specifically, or to non-motorized movement. Its effects on road users can include travel time, cost, and access. The time impacts can vary within different time scales related to reliability and congestion. Cost impacts can include vehicle operating costs and out-of-pocket costs. Access issues can determine mode availability, disabled access, and land use. The most common mobility performance measures are expressed as travel time or speed.

Proposed federal rules include the following measures (FHWA 2016):

- Reliability (23 CFR 490 Subpart E):
    - Percent of the Interstate System providing for reliable travel times
    - Percent of the non-Interstate NHS providing for reliable travel times

- Travel time efficiency (23 CFR 490 Subpart E):
    - Percent of the Interstate System where peak hour travel times meet expectations
    - Percent of the non-Interstate NHS where peak hour travel times meet expectations

- Freight movement (23 CFR 490 Subpart F):
    - Percent of the Interstate System mileage providing for reliable truck travel times
    - Percent of the Interstate System mileage congested

- Congestion (23 CFR 490 Subpart G):
    - Annual hours of excessive delay per capita

These measures are subdivided by interstate or non-interstate NHS, but agencies can choose any other subnetworks as needed to satisfy their internal decision making requirements. All of the federal measures are computed by first classifying road segments into categories analogous to (but not exactly the same as) acceptable and unacceptable according to travel time or speed. The total length or total delay is then accumulated.

The federal measures are all derived from travel time estimates using HPMS data, which in the future will be available for all NHS roads but not necessarily for non-NHS roads. The AASHTO Red Book provides a standardized travel time cost in dollars per hour. With this research-based metric, it is relatively easy to convert any estimate of excess travel time into an estimate of social cost. Excess user costs in the form of vehicle operating cost or out-of-pocket cost can be directly added to this travel time cost.

4.5.1 VARIABLES AFFECTING DISRUPTION PROBABILITY AND TRAVEL TIME OR COST

In all of the performance management decision contexts discussed above, and in particular for project evaluation and priority setting, the significant aspect of travel time is excess or avoidable time: or the time savings if a project is implemented. The same can be said for excess travel cost.

Properties which affect mobility in an asset-specific way include the following:

Pavements:

- Excessively rough pavements may force all traffic to reduce speed and increase travel time.
- If pavement condition is sufficiently poor, some traffic may be forced to detour, incurring excess travel time and vehicle operating cost.

Bridges:

- Excessively rough deck wearing surfaces or expansion joints may force all traffic to reduce speed and increase travel time.
- If clearance or load capacity are restricted, certain classes of trucks may be forced to take an alternate route, incurring excess travel time and vehicle operating cost.
- If a bridge is damaged by an adverse event such as an earthquake or flood, all traffic may be forced to detour.
- If a bridge is closed and no detour route is available, a mode shift may be necessary, resulting in out-of-pocket costs (such as ferry tolls or airfares).

Roadway embankments:

- An embankment washout, which can be caused by scour, flooding, culvert blockage, erosion at culvert joints, or other phenomena, may force all traffic to detour or shift modes.
- Excessive frost heave may force all traffic to reduce speed and increase travel time.

Traffic signals:

- Failure of the signals at an intersection may force 4-way stop operations, reducing intersection capacity and increasing travel times.

Sidewalks:

- Lack of accessible ramps, or slab faulting and settlement, may render a sidewalk unusable for wheelchairs.

Some of these asset-specific properties are condition-related (i.e. they deteriorate over time); some are resilience-related (i.e. they affect the likelihood of sudden unexpected service disruption); and some relate to functionality (e.g. clearances and load ratings). Mobility deficiencies may also relate to the roadway as a whole, as in the case of congestion due to insufficient lane capacity (or excess demand). In all of these cases, the effect on road users is an increase in travel time and/or cost.

Software used by FHWA for investment analysis, in particular HERS and NBIAS, contains models intended to address many of these issues by estimating avoidable time and cost. For bridges, states are required to estimate detour distances as part of the National Bridge Inspection Standards, and many states can do so using their geographic information systems. Florida DOT has developed truck height and weight histograms used in the estimation of avoidable truck time and cost due to clearance and load restrictions (Sobanjo and Thompson 2001). Many pavement and bridge management systems have built-in functionality to estimate avoidable travel time and cost.

Once they have been estimated using asset-specific methods, excess time and cost are asset-generic concepts that can readily be summed to calculate network level performance across assets, in any context where a benefit/cost ratio is required. For level of service standards, agencies typically use asset-specific measures (such as IRI and vertical clearance) rather than methods based on travel time. However, for comparing two assets, for tracking an asset over time, or for setting asset-generic targets, the federal measures are a useful set of normalizations that enhance the management of mobility.

4.5.2 MONETIZING MOBILITY BENEFITS

Mobility consequences of hazards or functional deficiencies may entail detours while a bridge or road section is monitored, repaired, or rebuilt; or may have smaller impacts such as truck restrictions or speed reductions.

For detours, vehicle operating cost can be developed from the AASHTO Red Book, page 5-10. This includes fuel, oil, maintenance, and tires. Updated to 2016 dollars using the Consumer Price Index (BLS 2016), this cost is $0.208 per mile of excess distance if the “large car” column is used to represent general traffic. The truck value would be used for scenarios where only trucks are forced to detour.

Travel time cost can be developed from the AASHTO Red Book, page 5-4. This figure uses the average over all occupations, computed as an opportunity cost. Updated to 2016 dollars using the Consumer Price Index, this cost is $30.62 per hour.

Consequence estimates should account for average vehicle occupancy as developed for transportation planning purposes.

As is the case for safety, project benefits are always computed as the difference between two defined investment levels. The consequence estimate, therefore, should reflect only the time and distance avoided because of the choice. Out-of-pocket costs, defined in the same way, may be added if applicable.

4.6 ENVIRONMENTAL SUSTAINABILITY

FHWA's emissions measure focuses specifically on CMAQ-funded projects, but the concept of emissions reduction is applicable to a much wider range of TAM decisions. Any project that reduces detour miles will also reduce emissions. This includes risk mitigation projects that increase resilience and reduce the likelihood of service disruption. Decreases in congestion may also reduce emissions by allowing traffic to flow at a more efficient speed and reducing speed change cycles.

A very relevant approach is used in FHWA's Highway Economic Requirements System (HERS) (FHWA 2005, Appendix F). This methodology, updated from earlier research in California (Booz-Allen & Hamilton, Inc., 1999), relies on a study that simulates vehicular air pollution emissions under various scenarios of congestion, speed, and volume. Six pollutants are included in the analysis: carbon monoxide, volatile organic compounds, oxides of nitrogen, sulfur oxides, small particulate matter, and road dust. Estimates of speed and distance can be converted directly to emissions quantities using these models.

The Booz-Allen & Hamilton study uses earlier research on the economic impact on health and property damage caused by these pollutants, in order to convert the emissions estimates to dollars. This is valuable because decision makers typically do not have an intuitive sense of the relative hazards of different pollutants. Expressing all pollutants in tons may be misleading because the impacts on the public differ substantially among pollutants.

Emission damage cost is summarized in Table 9, based on the data provided in FHWA (2005). The FHWA report provides the cost estimates disaggregated by vehicle class – four-tire vehicles, single-unit trucks, and combination trucks. Therefore 2013 FHWA statistics on vehicle-miles travelled (FHWA 2015) were used to develop weighted averages. These were updated to 2016 dollars using the consumer price index (BLS 2016).

A limitation of the HERS method is that it does not consider carbon dioxide emissions, nor does it include noise or potential losses to water, agricultural, recreational, or cultural resources. These would be attractive areas for future research.

Table 9. Emissions damage costs (adapted from FHWA 2005).

Emission damage cost in 2016 $ per vehicle-mile															
		Detour speed (mph)													
	Functional class	5	10	15	20	25	30	35	40	45	50	55	60	65	70
1	Rural interstate	0.0805	0.0627	0.0548	0.0510	0.0478	0.0478	0.0472	0.0475	0.0484	0.0500	0.0525	0.0562	0.0616	0.0669
2	Rural Principal Arterial	0.0620	0.0437	0.0370	0.0330	0.0309	0.0297	0.0290	0.0295	0.0296	0.0303	0.0315	0.0333	0.0358	0.0382
6	Rural Minor Arterial	0.0619	0.0436	0.0369	0.0329	0.0308	0.0296	0.0289	0.0294	0.0295	0.0302	0.0314	0.0332	0.0356	0.0381
7	Rural Major Collector	0.0565	0.0386	0.0323	0.0288	0.0270	0.0258	0.0252	0.0254	0.0255	0.0259	0.0266	0.0275	0.0288	0.0301
8	Rural Minor Collector	0.0565	0.0386	0.0323	0.0288	0.0270	0.0258	0.0252	0.0254	0.0255	0.0259	0.0266	0.0275	0.0288	0.0301
9	Rural Local	0.0565	0.0386	0.0323	0.0288	0.0270	0.0258	0.0252	0.0254	0.0255	0.0259	0.0266	0.0275	0.0288	0.0301
11	Urban Interstate	0.0500	0.0363	0.0312	0.0294	0.0284	0.0277	0.0274	0.0275	0.0279	0.0286	0.0296	0.0311	0.0333	0.0355
12	Urban Freeways	0.0407	0.0276	0.0232	0.0220	0.0213	0.0208	0.0205	0.0205	0.0207	0.0210	0.0215	0.0221	0.0229	0.0238
14	Urban Principal Arterial	0.0416	0.0286	0.0246	0.0222	0.0208	0.0200	0.0195	0.0196	0.0198	0.0201	0.0206	0.0212	0.0221	0.0231
16	Urban Minor Arterial	0.0413	0.0284	0.0245	0.0221	0.0207	0.0198	0.0194	0.0194	0.0196	0.0199	0.0204	0.0210	0.0219	0.0228
17	Urban Collector	0.0413	0.0284	0.0244	0.0220	0.0206	0.0198	0.0193	0.0194	0.0196	0.0199	0.0203	0.0210	0.0218	0.0227
19	Urban Local	0.0413	0.0284	0.0244	0.0220	0.0206	0.0198	0.0193	0.0194	0.0196	0.0199	0.0203	0.0210	0.0218	0.0227

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CHAPTER 5. RECOMMENDED METHODOLOGY

Given the framework, data resources, and tools presented in the earlier chapters, this chapter pulls it all together into a recommended methodology to enable full implementation of a comprehensive TAM Plan. The methodology considers all of the performance goals and management concerns that are required to be addressed in TAM Plans, and provides room for agencies to add their own goals as needed. It provides the necessary means for agencies to set performance targets, and to structure TAM business processes that make progress toward the targets in the near-term and long-term. It is sufficiently general to support all infrastructure asset classes while representing the unique ways that each asset affects performance.

The methodology overcomes the limitations of NCHRP Report 806 in that it is able to fully consider inter-temporal tradeoffs, able to handle multi-agency decision making and stakeholder turnover, and can accommodate corridor-level transportation plans and other outcome-based stakeholder requirements. Compared to the Report 806 methodology, the recommended scheme relies more on published research and less on judgment, but is still able to accommodate non-quantitative factors in decision making.

5.1 OVERVIEW OF FRAMEWORK

Figure **13**, which is repeated from Chapter 1, shows the major concepts and their logical flow. Several aspects of the diagram will be important in the methodology:

- The concept of project benefit is essential, as the means of integrating all relevant asset classes and stakeholder concerns in the tradeoff analysis. In the past, the term “benefit” has been used loosely or ambiguously in the asset management literature, much as the term “performance” has often been unclear. The methodology relies on a more precise set of definitions for this important concept, relying on the concept of avoidable cost, where cost is always measured in dollars.
- Benefit is the difference in long-term social cost between two defined alternatives, where one alternative represents doing nothing during a decision interval. Long-term social cost includes the agency costs of the project under consideration, all future projects affecting the same assets, and the costs associated with replacement and successor assets. It also includes the user and non-user costs of functional deficiencies and risk. Functionality and risk can affect any or all of the stakeholder concerns.
- Each asset has a set of characteristics affecting cost, functionality, and risk. Forecasts of future condition, resilience, and utilization can change the cost, functionality, and risk. If a project is delayed, all of these characteristics and concerns can change.
- The standards for describing assets, and their condition and resilience, can be specific to asset classes, as they are in pavement and bridge management systems. The models for long-term cost (including deterioration and cost estimation), functional deficiency costs, and risk are also asset-specific. The results of these calculations, in the form of avoidable agency cost, avoidable crash counts, avoidable travel time, avoidable user cost, and

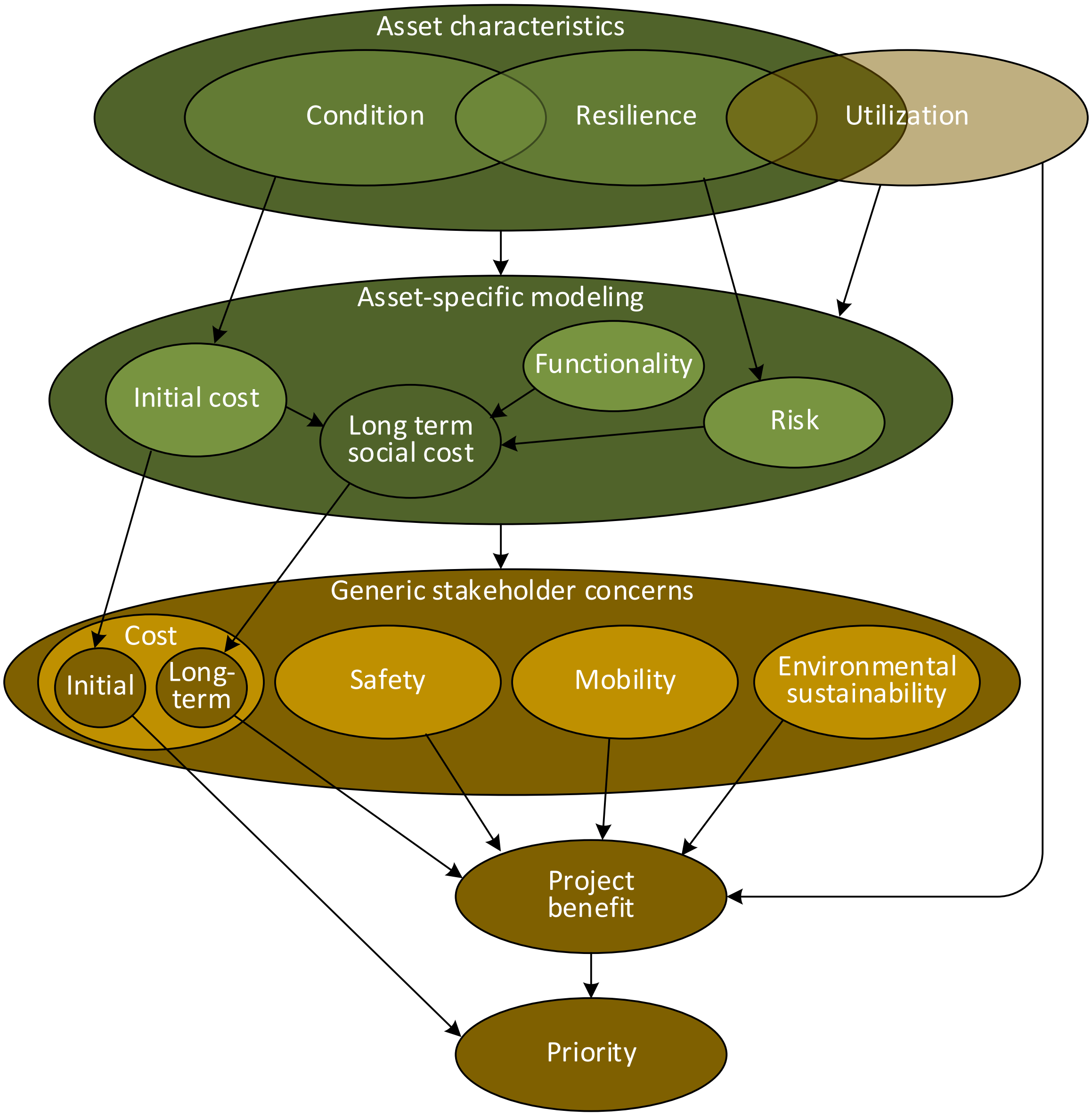

Figure 13. Recommended performance management framework.

avoidable environmental cost, are all asset-generic in the way they are defined and used in the benefit calculation.

- Asset-specific performance measures can be computed and are useful for some purposes such as levels of service and treatment feasibility criteria. But the tradeoff analysis and the performance measures it consumes and produces are asset-generic.
- The tradeoff analysis is designed to take place outside any asset-specific management system. All of the project alternatives to be considered are generated in advance by the management systems, and then the tradeoff analysis narrows down the list. Although, it is not necessary to feed results back into the management systems, doing so can enable the agency to use the results further in asset-specific processes. The analysis may entail a

feasible number of alternative life-cycle activity plans for each project with benefits and costs computed over a long-term analysis period.

In the diagrams in this chapter, processes shown in green are typically asset-specific, meaning that the methodologies can differ by asset class and use performance measures whose definitions might not be consistent across asset classes. Processes shown in brown, on the other hand, are asset-generic and can apply consistently to any or all asset classes.

5.2 ESTIMATING LONG-TERM BENEFIT

The proposed methodology is based on the premise that all TAM decisions are to be made in a way that selects from among relevant alternatives the one that maximizes long-term benefits. The definition of relevant alternative depends on the nature of the decision to be made; the significant decision contexts will be addressed in Section 5.3. The emphasis on long-term ensures that all relevant inter-temporal tradeoffs are considered. Benefit is carefully defined to include the effects of decisions on all relevant performance goals and management concerns.

Figure **14** shows an overview of the benefit calculation. Two parallel alternatives are considered: a candidate to be evaluated, and a null alternative. The Candidate Project represents an investment that the decision makers wish to consider. Although it is convenient to think of this as a potential project, it might represent just a part of a project, such as a single-asset work item or even an element of an asset (such as repair of a bridge expansion joint). It might also represent a set of investments on a group of assets. The same methodology is proposed for all these potential applications.

The null alternative represents a baseline set of choices, against which the candidate is to be compared. This alternative can be defined in different ways in different agencies for different decision contexts; the important thing is to define it consistently in a manner that reflects the realistic alternatives. Considerations in choosing a definition include:

- If the definition relies on relatively few interventions, it requires relatively little computational effort.
- If the definition results in higher social costs than any realistic candidate the agency is likely to select, then all benefits will be positive or at least non-negative, which simplifies usage and interpretation of results.
- Some of the quantities used in the calculation are more easily determined on an incremental, rather than total, basis. For example, it is more difficult to estimate the total number of accidents on a road segment than to estimate the incremental change in accidents caused by a proposed treatment. Crash rates depend on characteristics of the driver, vehicle, and road, but usually TAM decisions concern only the road. For this reason, it is more common in TAM to measure safety performance in terms of excess crashes rather than total crashes.

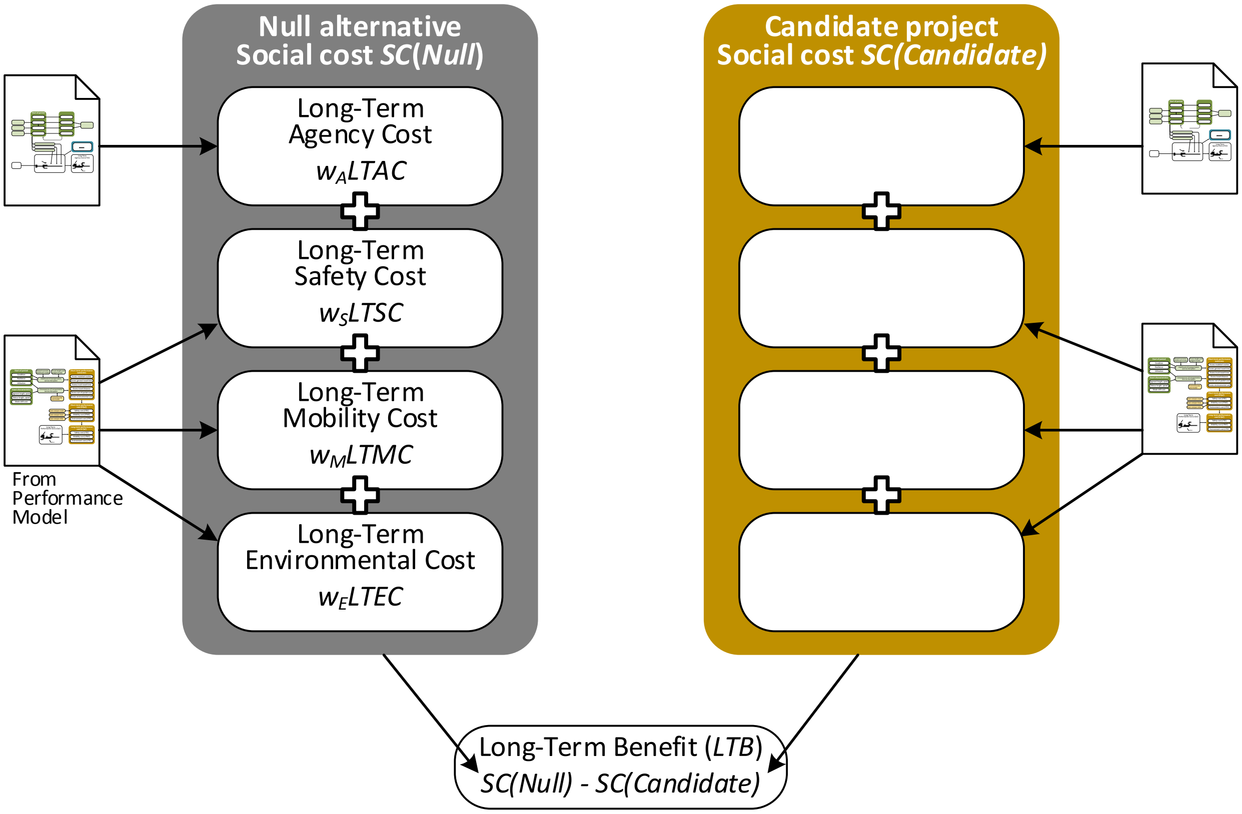

Figure 14. Overview of long-term benefit calculation.

For needs estimation, a common and relatively simple way to formulate the null alternative is to consider a policy of replacement-only: the agency takes no action to extend service life, improve functionality, or mitigate risks, but merely allows the asset to deteriorate until it must be replaced in order to keep the road open. Note that the hypothesis testing framework can be easily extended to include comparison of multiple alternatives, such as delaying an action by specific time intervals. Figure **15** compares a typical candidate condition profile with a replacement-only alternative.

The social cost of each alternative is made up of four factors representing four major stakeholder concerns: cost, safety, mobility, and environmental sustainability. Agencies may choose to subdivide these or add more concerns if their enabling legislation or strategic plans call for it. The long-term cost factors *LTAC*, *LTSC*, *LTMC*, and *LTEC* (collectively, *LTpC* for short) are computed as described below. Each has a weight w_p. Since all of the LTpC quantities are in dollars, by default they all have the same weight, $w_p = 1.0$, under the premise that in a market economy each dollar has the same value whether spent by the agency, the taxpayer, or the road user. However, decision-makers may want to vary these weights, for several reasons:

- Agency strategic plans may have explicitly declared that certain performance objectives should have more importance than others.

- Forecast outcomes, using the uniform weights of 1.0, might not accomplish desired objectives or pre-existing targets.
- Statewide or municipal transportation plans may call for increased emphasis for certain objectives in certain corridors, geographic areas, or networks.
- The agency may wish to accelerate the accomplishment of a specific objective.
- In a multi-agency decision making context, different agencies may have different sets of strategic objectives, different targets, or different policies.

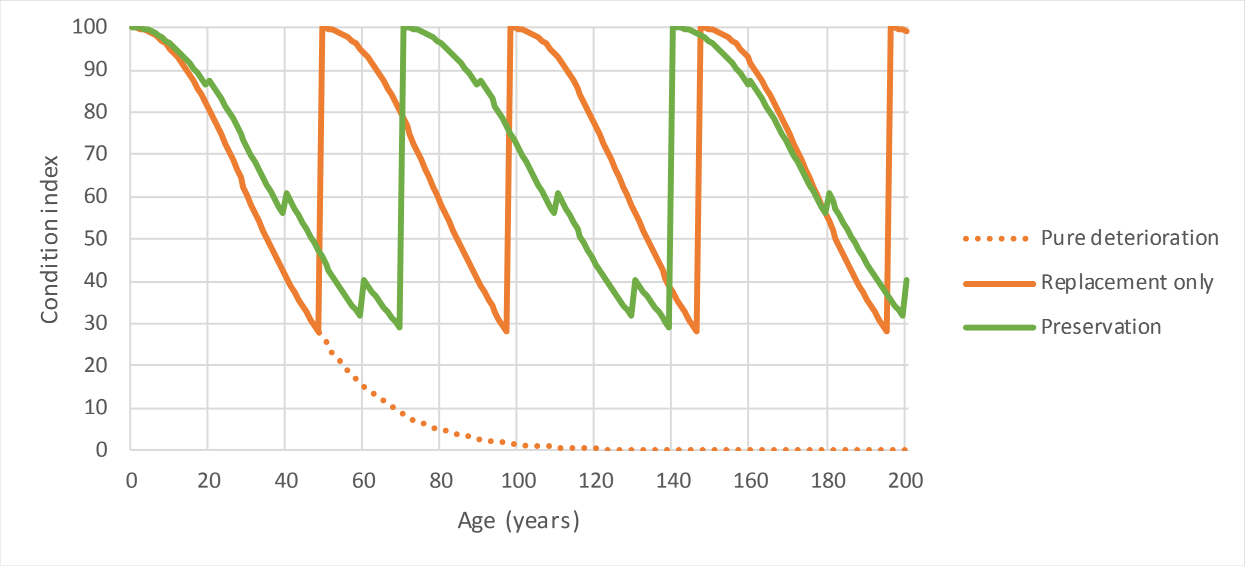

Figure 15. Comparing long term condition profiles of a candidate project and null alternative.

Decision makers will not necessarily know, in advance, whether weights other than the default 1.0 should be used. There is no evidence that any stakeholder would know what a reasonable weight should be *a priori*, nor is there evidence that objective weights would be revealed by a subjective preference poll such as the Analytic Hierarchy Process. Carrying out a full analysis and seeing the forecast outcomes provides a much stronger basis for decision makers to see a need to adjust the weights. It also provides a necessary linkage between the target-setting process and subsequent decision making. The additive methodology shown in Figure **14**, with an obvious default value of 1.0 for each weight, provides a convenient starting point and an efficient, linear means of conducting "what-if" analysis to support dynamic group decision making driven by performance targets.

5.2.1 TREATMENT PLANNING MODEL

In Figure **14**, the estimates of long-term agency cost come from a separate Treatment Planning Model. This model is shown schematically in Figure **16**. The treatment planning model incorporates multi-year forecasting of condition, resilience, and utilization, which all affect the future selection of appropriate treatments. The model evaluates current conditions (from the most recent inspection, for example), selects appropriate treatments, and estimates their cost. Based on the effect of the treatment, the model proceeds to estimate future conditions, and may identify future treatments and their costs. It does this over a very long time frame. Taking into account the time value of money, the model discounts future costs and computes the net present value of all costs, current plus future.

The model depicted in Figure **16** is often called a life cycle cost model. For the current framework, however, it is more accurate to call it a long-term cost model because it addresses costs beyond the lifespan of the asset. It assumes that the need for the asset will continue to exist, so the asset is replaced once it reaches the end of its life. In most applications the model does not need to speculate about far future changes in demand or technology, but merely assumes that the asset is replaced with another asset having the same characteristics.

For convenience in making the computations, the time frame of the analysis is structured into periods, denoted using lower-case *y*, which are usually one year in length. In situations where computational performance is a concern, sometimes periods are five or ten years in length. The total length of the analysis, expressed as the number of periods analyzed and denoted with upper-case *Y*, depends primarily on the discount rate. It must be a sufficiently long time that further extension of the analysis is unlikely to affect any significant results. As discussed earlier, current draft TAM Plans tend to use discount rates in the 1.9 to 2.4 percent range, excluding inflation, and project long-term costs for 200 years. A replacement cost of $10 million, for example, 200 years in the future, has a present value of $190,531 at a 2% discount rate.

In a cross-asset analysis, a project may be composed of multiple asset classes having different lifespans. The length of the analysis should extend beyond the normal replacement interval of any assets that might be included. In Figure **16** it is therefore described as the “long-term horizon.” The point of such a long time horizon is not to make precise forecasts of the far future, but is rather to ensure that assets which are independently constructed and managed are all compared on a common, consistent basis.

The capabilities described in Figure **16** can be found in many pavement and bridge management systems. Often the models used for deterioration, treatment selection, and cost estimation can be quite sophisticated. For example, some pavement management systems use mechanistic models, and some bridge management systems separately analyze the elements that make up a bridge.

Methods for other asset classes can be found in NCHRP Report 713 (Thompson et al 2012) and in Alaska’s Geotechnical Asset Management Program (Beckstrand et al 2016). Without getting into the technical sophistication often found with pavements and bridges, a basic long-term cost model using Markovian deterioration can be very simple, implementable in a small spreadsheet. Such models have been used at the network level in the preparation of many states’ TAM Plans, including Minnesota, Ohio, Nevada, Texas, and Alabama. Figure **15**, above, is from one of these plans.

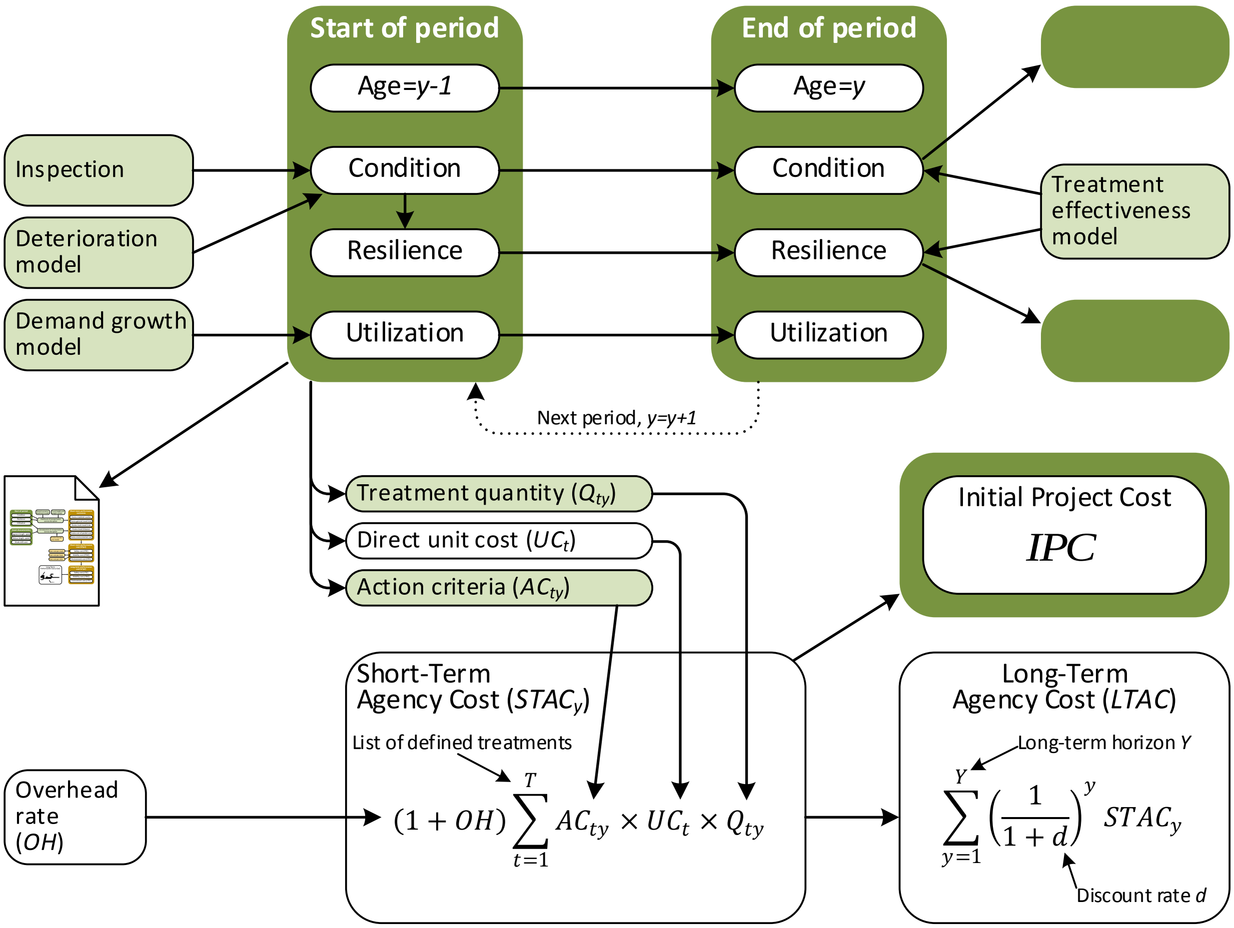

Figure 16. Treatment Planning Model.

In each period of the treatment planning model, the status of the asset(s) is updated to forecast condition, resilience, and utilization at the start of the period. A set of decision rules determines an appropriate set of actions, and estimates their cost and effect. In pavement management systems, the action criteria may consist of decision trees leading to selection of a single treatment. In bridge management systems, each condition state of each element has a list of feasible actions: Pontis selects its actions using a network optimization model for each element, while AASHTO's upcoming BrM software selects the treatments that minimize the long-term cost of the project overall. In general, action criteria can consist of:

- Level of service standards to select replacement, functional improvements, or risk mitigation;
- Preservation criteria, based on condition, to select preservation actions;
- Mitigation criteria, based on resilience characteristics, to select risk mitigation or functional improvement actions.

Most asset management systems have level of service criteria, minimum project size criteria, and other rules which serve to suppress unrealistic projects. Long-term cost models typically do not attempt to align the needs on separate parts of a project so that they occur at the same time, as that would assume more precision than is generally feasible with these predictive models.

Separate parts of an asset can be analyzed using completely separate models. As long as they use the same discount rate and the same long-term horizon, the resulting present value costs can simply be added together. In long-term models indirect costs are represented by an overhead rate applied to direct costs, so they are additive as well.

5.2.2 PERFORMANCE MODEL

Estimates of performance and the corresponding social costs can be produced with a set of models such as the ones depicted in Figure **17**. These models build on the same forecasts of condition, resilience, and utilization that are developed period-by-period in the Treatment Planning Model.

Condition and resilience are used in conjunction with hazard scenario likelihood models to estimate the likelihood that transportation service will be disrupted by an adverse event. Such models are found in bridge management systems (Sobanjo and Thompson 2013) and in geotechnical asset management (Beckstrand et al 2016). NCHRP Project 20-07(378) is developing a guideline for use with AASHTOWare Bridge Management, that is also applicable to other asset classes. Truck height and weight models can be used to estimate the fraction of trucks that must detour around a bridge, and the probability that an over-height or overweight truck might damage a bridge (Sobanjo and Thompson 2013).

The consequences of a service disruption or functional deficiency depend on asset utilization and other asset characteristics. For scenarios that might interrupt service of an asset entirely, the characteristics of alternate routes and/or modes are also significant.

Performance outcomes can be described directly in terms of metrics important to road users or stakeholders, such as crashes, time, distance, and cost. Level-of-service criteria can be applied to these measures to characterize an asset or road segment as acceptable or unacceptable. Recent FHWA rule-making (FHWA 2016) proposes a set of methods to do this. Performance of a network or any group of assets can be described by summing these performance outcomes, or by summing the quantity of asset found to be acceptable according to the level of service criteria.

For communication and target-setting, level of service criteria are useful in this context because they can be developed from customer survey data or other information about road user preferences, and can vary among parts of the network.

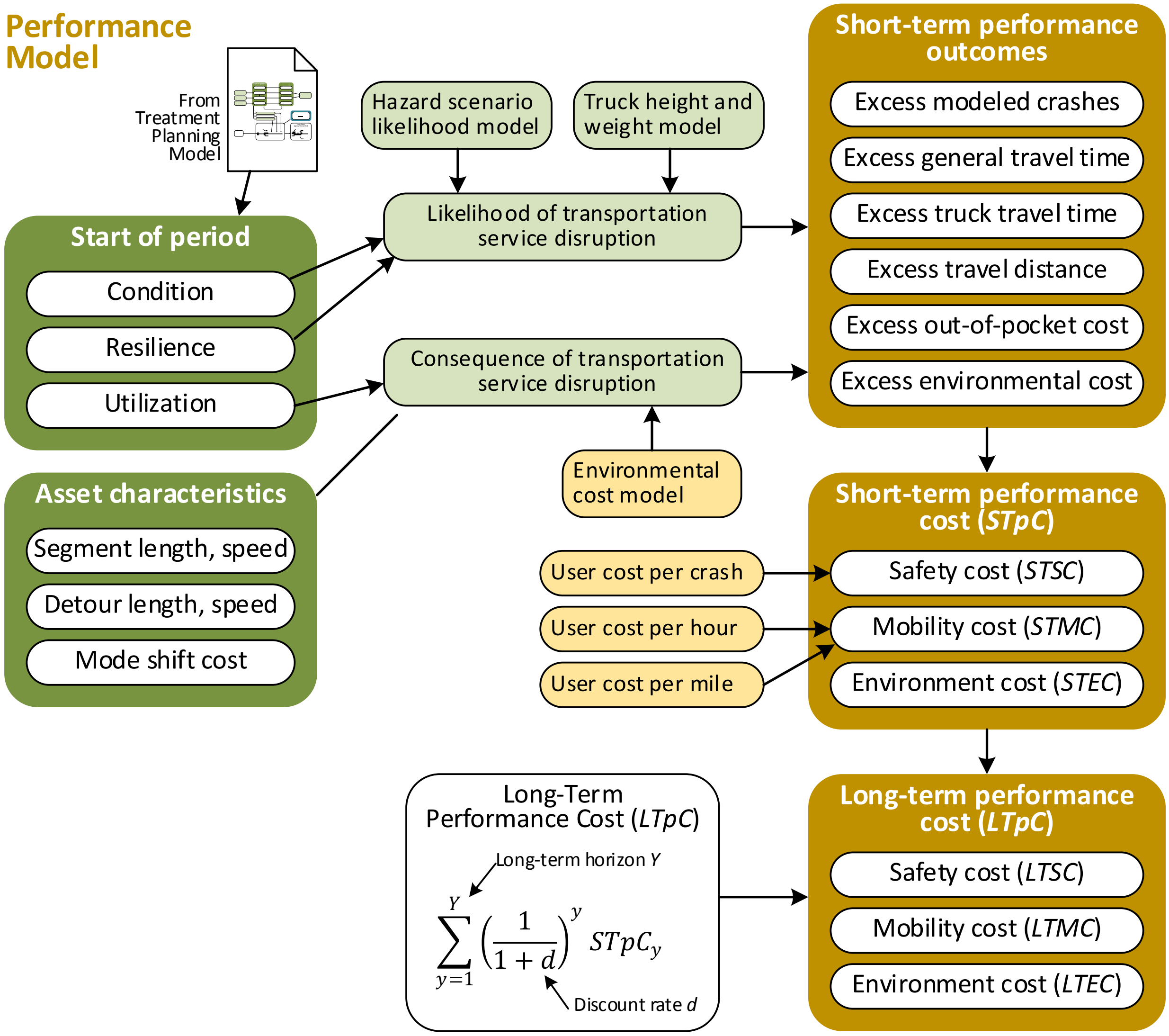

Figure 17. Performance Model.

Performance metrics can be converted to cost using AASHTO's Red Book (AASHTO 2010). The Red Book is commonly used in a variety of applications where service characteristics have cost implications: for example, contractual early-completion incentives, analysis of design alternatives, and the determination of cost-effectiveness of operational strategies (Markow 2012).

Short-term performance cost is computed separately for each period, and depends on the treatments that were selected in previous periods. Over the years leading up to the long-term horizon, the discounted sum of all these costs is a long-term social cost that feeds back into the benefit calculation.

Some pavement management systems and bridge management systems have capabilities to compute some or all of the performance metrics shown in Figure **17**. FHWA planning tools such as HERS and NBIAS also have these capabilities. NCHRP Report 590 (Patidar et al 2007) shows how these common models can be implemented in Excel worksheets. Since all of the costs are additive, it is possible to supplement the functions of existing management systems using spreadsheet calculations of any portions of the analysis that are not already covered in agency systems. The conversion of performance outcomes to performance costs is asset-generic and can be performed as part of a cross-asset tradeoff analysis operating on an Investment Candidate File.

5.3 DECISION-SENSITIVE NETWORK LEVEL TRADEOFF ANALYSIS

Decision making requirements determine the definition of benefits in Figure **14** above, specifically the definition of the Null Alternative. A network-level or program-level tradeoff analysis is composed of a set of project-level decisions from among two competing alternatives. The Candidate Project represents a decision to implement an investment, and the Null Alternative represents a decision not to implement the investment.

The Null Alternative should be based on a reasonable and consistent set of assumptions about what will happen if the investment is not made. In most cases this means doing nothing in the near-term, and then making the most appropriate decision at the next opportunity. The Null Alternative could also entail deferring the investment by a specific period or preferring a feasible less expensive alternative which necessarily is not the most cost effective in the long term. The delay will generally cause deterioration of condition and resilience, degradation of performance, and increase in cost. These impacts are all considered as part of candidate projects developed for the following year. This means that the benefit calculation in Figure **14**, Figure **16** and Figure **17** is repeated for each possible implementation year in which action criteria are met.

For all of the decision making applications addressed in this methodology, Figure **18** shows the general pattern of the analysis, as a set of nested iterations. The outermost iteration involves testing a set of decision scenarios, which are typically alternative answers to a question involving network level tradeoff analysis on a multi-year time scale. For each scenario, the potential investments are analyzed year by year, to match the typical situation of annual funding constraints. Some agencies have biennial funding constraints, and may prefer to conduct this analysis in two-year increments.

Most of the decision scenarios are fiscally constrained, so they require setting priorities among a set of incremental investments. Each incremental cost added to a program should be chosen in a manner that maximizes network benefit. The pattern therefore reflects diminishing marginal returns as discussed in Chapter 2. An investment must satisfy action criteria and benefit criteria in order to be selected. If selected, the investment contributes to a running tally of annual costs and performance outcomes.

After a complete decision scenario is evaluated, the outcome is compared with the decision objectives. If the objectives are reached, then the process concludes; otherwise, additional scenarios are considered.

Several parts of Figure **18** depend on the decision-making context, which depends on the TAM business process to be supported. Table **10** lists the most common applications of cross-asset tradeoff analysis, showing how the ingredients of Figure **18** would be calculated in each case.

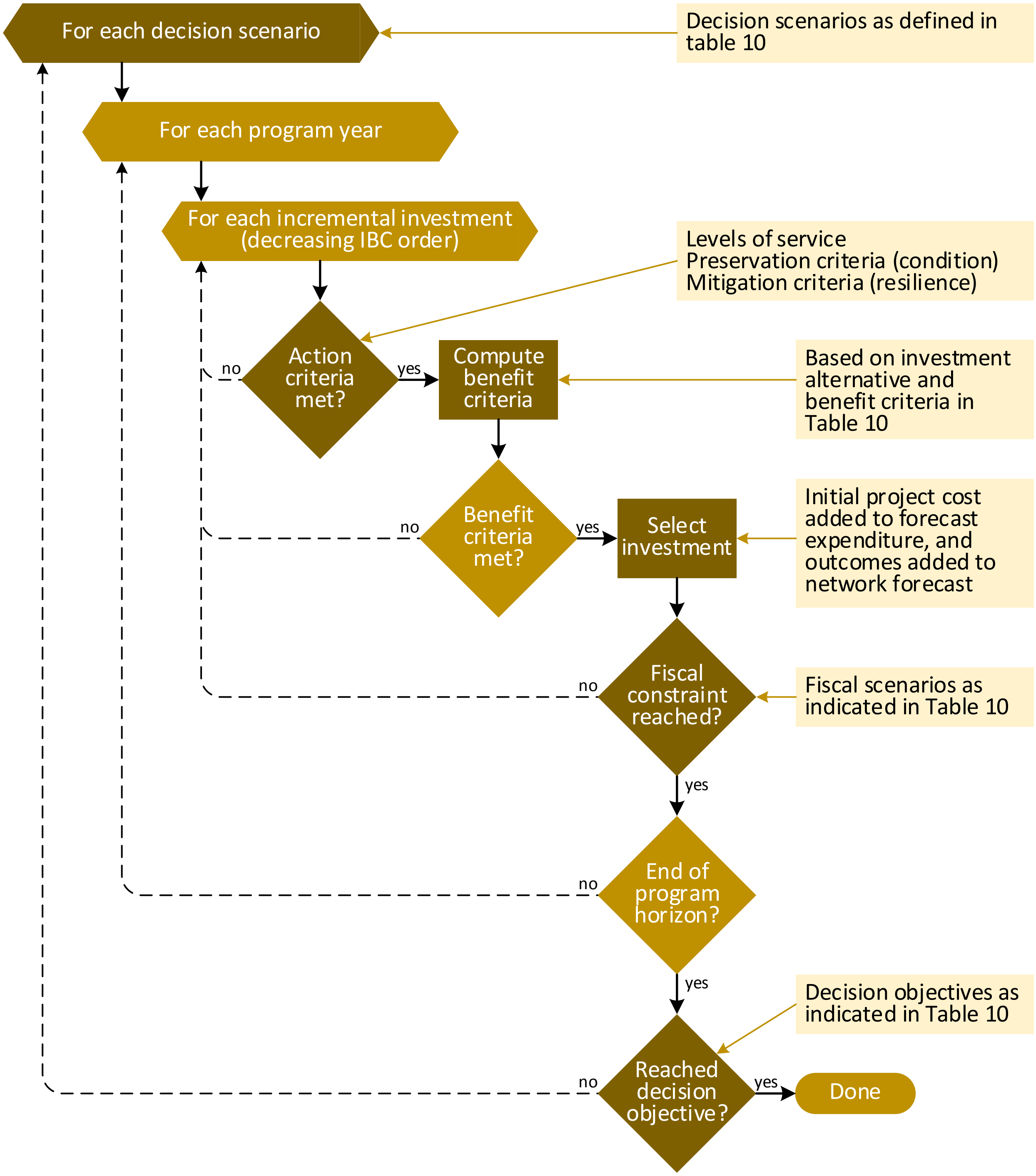

Figure 18. Decision support methodology – general search pattern.

Table 10. Decision-sensitive search parameters.

Decision	Decision scenarios	Null alternative	Benefit criteria	Fiscal scenarios	Decision objective
Needs estimation at a point in time	Single unconstrained scenario.	Replace only	Benefit > 0	Unconstrained	Complete all currently-available cost-effective actions meeting all level of service, preservation, and mitigation criteria.
Needs estimation or funding level within a program horizon	Alternative total multi-year funding levels (excluding inflation).	Delay past the end of program horizon	IBC >= Marginal IBC each year	Variable from optimistic to level where program objectives achieved.	Complete all available cost-effective actions meeting all level of service, preservation, and mitigation criteria including future new needs.
Levels of service and resilience criteria	Alternative level of service thresholds for project screening.	Delay past the end of program horizon	IBC >= Marginal IBC each year	Optimistic fiscal scenario	Make level of service criteria more economically consistent and realistic.
Priority programming	Alternative fiscal constraints to evaluate acceptability of outcomes.	Less-expensive alternative or 1-year delay	IBC >= Marginal IBC each year	Anticipated fiscal scenario plus over-programming margin	Maximize overall achievement of stakeholder objectives where funding may be variable.
Resource allocation	Alternative benefit weights for stakeholder concerns and/or parts of the network.	Less-expensive alternative or 1-year delay	IBC >= Marginal IBC each year	Anticipated fiscal scenario	Maximize equity and sub-network planning objectives.
Setting targets	May entail adjustment of fiscal constraints or benefit weights from year to year to obtain acceptable outcomes.	Less-expensive alternative or 1-year delay	IBC >= Marginal IBC each year	Conservative fiscal scenario	Set outcome expectations for 2-year, 4-year, and 10-year time horizons.
Evaluate target feasibility	Consider alternative planning metrics (e.g. deterioration rates, unit costs) within reasonable range of uncertainty.	Less-expensive alternative or 1-year delay	IBC >= Marginal IBC each year	Anticipated fiscal scenario	Accomplish a set of pre-existing targets.
Tracking and updating targets	May entail adjustment of fiscal constraints or benefit weights from year to year to obtain acceptable outcomes. May be necessary to change the targets.	Less-expensive alternative or 1-year delay	IBC >= Marginal IBC each year	Conservative fiscal scenario	Accomplish a set of pre-existing targets.
Add a task to a project	Alternative groupings of investments into projects.	Delay the added task past deferment period	Change in benefit > 0	Anticipated fiscal scenario	Improve efficiency or effectiveness of program.

The applications are described in the following sections.

5.3.1 NEEDS ESTIMATION AT A POINT IN TIME

This analysis estimates the total cost of all cost-effective work that could be done, based on a snapshot at a point in time of all aspects of condition, resilience, and performance. Usually this is based on the most recent inspections, and may be used as an all-encompassing status measure of the network. The benefit calculation in Figure **14** takes initial cost into account and is therefore a net benefit. Any value greater than zero denotes a cost-effective project.

In some applications this quantity is referred to as the backlog of work. It should be noted, however, that it includes new needs that arose in the year immediately before the inspection, which some people would not consider to be part of a backlog.

5.3.2 NEEDS WITHIN A PROGRAM HORIZON

Estimates of the backlog or instantaneous needs at a point in time can be misleading if audience members imagine spreading the needs out over a multi-year period. In the context of a time horizon, it is not enough to estimate current needs, because if any of these needs are not implemented right away there will be cost escalation (separate from inflation), and new needs will arise. The magnitude of these additional costs will depend on how much delay is built into the scenario, or how far into the future current needs are spread. This, in turn, depends on a fiscal scenario. The key project-level tradeoff is whether to satisfy a need within the program horizon, or after.

If the fiscal constraint is variable, the decision maker will want to increase the funding level until all level of service goals, preservation needs, and mitigation needs are satisfied within the program horizon. This type of analysis might be used to communicate the magnitude of a funding shortfall or an upper bound on beneficial expenditures. This is useful as a benchmark that legislators or funding bodies can use in evaluating the sufficiency of a new funding source. In any fiscally-constrained scenario, it is desirable to give highest priority to investments with the highest long-term benefit relative to the amount of money spent. This is quantified using the incremental benefit cost ratio (IBC) as discussed in Chapter 2. When two or more project candidates are available, the IBC of each candidate is computed based on the change in benefit and change in cost relative to the next less expensive alternative, provided that all the alternatives are on a curve of diminishing marginal returns.

In Figure **18**, investments are evaluated in IBC order, from highest to lowest, until the fiscal constraint is reached. The IBC of the final selected investment is the marginal IBC for the year. If a new need arises, perhaps triggered by a newly-completed inspection, the candidate can be added to a program-year if its IBC is greater than the year’s current marginal IBC. This is referred to as the benefit criterion for including a candidate project in the needs list.

5.3.3 LEVELS OF SERVICE, CONDITION, AND RESILIENCE CRITERIA

Most agencies have level of service standards for performance and risk, but these are not always based on rigorous analysis. The AASHTO TAM Guide (Gordon et al 2011) recommends the use of survey data to learn about customer preferences. Example methods can be found in NCHRP Report 511 (Hyman 2004) and NCHRP Report 590 (Patidar et al 2007). The more advanced Analytic Hierarchy Process found in NCHRP Report 806 (Maggiore et al 2015) can be used, but Report 590 also investigated this method and found that it did not significantly improve decision maker acceptance over simpler methods.

Any method based on survey data is likely to be subjective, so the agency may want to evaluate, and possibly adjust, level of service criteria to reflect economic consistency, or to produce more realistic needs estimates. For example, if an agency performs a seismic needs assessment and finds total needs are ten times the expected level of funding, it may want to tighten the resilience criteria so that the needs estimate is smaller and more consistent with other classes of needs. The degree of tightening required is itself a useful way of communicating the added risk implied by funding constraints.

In proposed rule-making, FHWA has adopted an approach similar to levels of service, to characterize pavement and bridge condition. These are asset-specific measures because the definitions of Good and Poor differ according to asset-specific conditions and concerns. In a next-generation set of measures, the definitions of Good and Poor could be made more generic using an economic concept such as treatment feasibility. For example, an asset might be in Good condition where preservation work (excluding routine maintenance) would be too early to be cost-effective in terms of agency costs and user dis-benefits; it might be in poor condition if condition is so deteriorated that preservation is no longer feasible. Such a definition could be extended to other asset classes beyond pavements and bridges.

The National Bridge Inventory condition ratings do not provide much latitude to create this type of definition, but the NBI element conditions are much more suitable. A panel of experts could be convened from a group of states, and asked to classify element condition states in this way.

Then a set of test questions could be posed in order to determine the ranges of extent of each condition state that would qualify a bridge in its entirety to be Good or Poor from both user and long-term cost perspective. This is similar to the Analytic Hierarchy Method of NCHRP Report 806, but would be mathematically simpler. A similar sort of expert elicitation could be performed for pavement distresses.

A group of states, led by Michigan, is currently conducting an FHWA pooled-fund study on the use of element level condition data in the management of large bridges. One of the issues that has been identified is that big bridges are counted as an indivisible unit in federal performance measures, with significant weight based on deck area. In most agencies these bridges are not managed indivisibly, and might not be uniform in their condition, resilience, or performance. Agencies would likely want to subdivide each big bridge into segments and compute levels of service and action criteria separately for each segment. Similar issues are less likely to arise for other asset classes, which are more uniform in size.

5.3.4 PRIORITY PROGRAMMING

The essential decision in program level analysis is the scheduling of individual investments in a manner that makes best use of the funding available each year. Decisions within the STIP time frame are especially important, but the analysis can be extended to the TAM Plan time frame in order to develop and track performance targets. The fiscal constraint may have a range of uncertainty. In addition, the agency will typically want to add room for over-programming, in order to ensure that project delays do not decrease the total amount of funding available. Fiscal constraints are applied year-by-year (or biennium by biennium in some agencies), with uncertainty increasing over time into the future. If an investment cannot be implemented in a given year due to the fiscal constraint, and no less expensive alternative is available, the null alternative is to delay the work for one year, then consider the investment again (including escalation due to deterioration and traffic growth) in the following year.

If an asset is in relatively good condition, it is possible that allowing it to deteriorate will introduce new preservation opportunities that can reduce long-term costs. In this case, delay of the investment might reduce long-term social cost. The incremental benefit of immediate work on this asset might be negative in that case, and the optimal timing of the work might be in the future. The analysis would not select work on the asset until the incremental benefit becomes positive, and might further delay the work until the asset moves sufficiently high on the priority list to fall within the fiscal constraint.

It is possible for an agency to have more than one program, where each program has separate eligibility criteria, fiscal constraints, and performance weights. For example, a safety program might fund only safety-related improvements. With multiple programs, each candidate investment is evaluated separately using the criteria and weights of each program. The program giving the highest benefit is the one whose objectives are the best fit to the candidate project.

5.3.5 RESOURCE ALLOCATION

Many stakeholders will want to evaluate programs not only on the acceptability or consistency of objective weights, but also based on equity of outcomes and accomplishment of localized planning objectives. If these concerns did not exist, resource allocation would be a simple matter of adding up programmed costs each year for each subdivision of the program or network. Realistic applications will need to establish sub-network objectives and evaluate these individually. The methodology allows decision makers to change the benefit weights as needed in order to influence program outcomes. The effect of the modified weights can be evaluated by comparing the weighted and unweighted benefits and priorities.

5.3.6 SETTING TARGETS

Targets represent measurable objectives that decision makers believe the agency can accomplish in a specified time period under a specified fiscal constraint. TAM Plans typically look ahead ten years, but proposed federal rules also require looking ahead 2 and 4 years to establish benchmarks on the way toward longer-term objectives. Targets are computed using the same process as programming and resource allocation, but agencies have typically used a more conservative fiscal scenario with no over-programming.

5.3.7 EVALUATING TARGET FEASIBILITY

This process involves re-evaluation of pre-existing targets, predicting outcomes in the same year for which the targets were originally developed. It may also involve evaluation of the feasibility of stakeholder-generated scenarios or communication strategies. For example, a decision maker might ask how likely it is that current funding is adequate to maintain current conditions. This exercise may entail adjustment to benefit weights, and sensitivity analysis of planning metrics such as deterioration models and costs, to determine the effect of uncertainty.

5.3.8 TRACKING AND UPDATING TARGETS

On two-year intervals, the agency will compare target vs actual performance and investigate the implications for achievement of the longer-term targets. If any aspect of performance is off-target, the agency may wish to modify planning metrics, benefit weights, or resource allocations. Year-to-year adjustments might be necessary to bring forecast outcomes back into alignment with targets over time. If a pre-existing target is found to be infeasible or not sufficiently conservative, the agency may decide to change the target.

5.4 OPTIMAL PROJECT SCOPING

Although there is a logical order to the business processes presented in Figure **1** and Table **10**, in reality these processes run in parallel. At the same time that the agency is developing its STIP and updating its TAM Plan, it is also gathering new inspection data and developing new projects. This makes it important that the methodology can incorporate project-level cross-asset needs and priorities, and that project scope can be optimized without losing compatibility with the rest of the analysis.

In a long-term analysis it is sufficient for all calculations to be performed at the asset level. Within the STIP horizon, however, some fine-tuning may be desired. For example:

- Because of the cost and disruption of work zone traffic control strategies, agencies will often want to address the needs on as many assets as possible that can take advantage of the same traffic control scheme.
- Once a section of road has been disrupted by a work zone, the agency will endeavor to avoid returning to that road section again for some extended period of time, perhaps ten years. Any new needs that arise will be deferred until this period expires, so it is often known as the “deferment period.” Pavement and bridge management systems often make the deferment period an explicit part of the programming logic. In this situation, a decision to delay work within the affected area is equivalent to deciding to delay the work for the duration of the deferment period.
- There can be economies of scale if two nearby projects are implemented together. They may share a traffic control strategy, hauling of materials, mobilization of equipment, acquisition of land, environmental mitigation measures, and other indirect costs. A project with a negative long-term benefit according to Figure **14** might become positive if its incremental indirect costs can be made lower than what might be indicated by the overhead rate, by combining with a more attractive nearby project.
- Even within a single asset, such as a bridge, certain elements may have work with positive long-term benefits and some with negative LTB. The portions with negative

LTB might be made positive if they add relatively little to indirect cost. If these portions are not implemented, the alternative is to allow them to deteriorate for the length of the deferment period before being considered again. This deferred option might have considerably higher agency costs and social costs if forecast deterioration renders preservation infeasible.

These kinds of tradeoffs can be evaluated using the cross-asset social benefit analysis described here. Provided there is at least one treatment with positive LTB computed as in Figure **14**, additional work tasks can be added to it if each one has a positive incremental LTB. Incremental LTB is determined as follows:

1. Compute LTB for each of the work tasks under consideration. Among the tasks with positive LTB, start with the one that is most likely to drive the overall project scope, including the work zone traffic control strategy.
2. For each additional work task under consideration, re-evaluate indirect costs in light of the decision in step 1. Compute the change in LTB if the item is added. If this change is greater than zero, then add it to the project.
3. Repeat step 2 to see if additional tasks can be added.

In Step 2, the change in LTB takes into account all of the assets that are part of the combined project being evaluated. It compares two alternatives as follows:

- The null alternative keeps the project defined as-is, and defers work on the new task until the end of the deferment period.
- The candidate alternative combines the new task into the project and does not defer the work.

Social cost is computed both ways, and the candidate is selected if it produces lower social cost than the null alternative.

Note that the method described in Figure **14** for computing LTB is the same for both alternatives; the difference is in how the null alternative is defined. The social cost calculation is asset generic, so any asset class can contribute to this decision. A few management systems, particularly AASHTOWare Bridge Management, have capabilities that support this type of decision. None, however, have such a capability that can work across asset classes.

5.5 GAUGING PROGRESS

All outcome-based performance measures are, in effect, backward-looking, because they measure the irreversible effects of decisions made in earlier years. To some extent the existence of 2-year and 4-year waypoints helps to reduce the decision lag, because agencies can make adjustments based on their rate of progress.

In presentations of condition, resilience, and performance to stakeholders and the public, clear communication of targets and progress toward targets is important. The performance measures that are useful in tradeoff analysis, such as cost, travel time, and modeled crash count, are difficult to communicate for individual assets or groups of assets. For this purpose, agencies typically normalize these quantities so they are more comparable among assets regardless of asset class or size. Several techniques can be used:

- Performance metrics can be normalized by dividing by vehicle-miles traveled (VMT): for example:
    - Excess travel time per VMT
    - Excess travel cost per VMT
    - Excess travel distance per VMT
    - Excess emissions cost per VMT
- Condition can be expressed in the form of a condition index, such as the bridge health index or pavement condition index. These indexes are widely used but they are not asset-generic: for example, a bridge health index of 80 is not equivalent in any way with a pavement condition index of 80. NCHRP Report 590 provides some methods for scaling these indexes so they are consistent and uniform. This is usually done by comparing index values with other quantities that are known to be uniformly scaled, such as life cycle cost.
- Level of service criteria can be established to separate acceptable from unacceptable, and the percent acceptable can be used as a performance measure. This is the method FHWA has selected in its proposed rule-making for most metrics. This option is most likely to be implementable in an asset-generic way, but it requires some degree of consistency in the definition of “acceptable” across asset classes. The methods described above for making levels of service economically consistent can help to overcome this concern.

None of these methods are very effective in communicating the degree to which an agency is following an optimal preservation or risk mitigation strategy. However, it is possible, using the methods described here, to determine the long-term optimal fraction of the inventory that is in acceptable condition but meets action criteria for preservation or risk mitigation. This fraction would vary among asset classes. An asset-generic way to quantify this is the optimal annual expenditure on preservation or risk mitigation, which is an output measure.

In fact, output measures are valuable across the board as leading indicators of future performance, provided that they are developed based on the same fiscal scenario and planning metrics as were used in setting the performance targets. The agency is on-track toward its targets if its expenditures are in line with the target setting analysis. Logical output-based performance measures would be:

- Annual expenditures directed to preservation, as a percent of required expenditures
- Annual expenditures directed to risk mitigation, as a percent of required expenditures
- Annual expenditures directed to safety improvement, as a percent of required expenditures
- Annual expenditures directed to mobility improvement, as a percent of required expenditures
- Annual expenditures directed to environmental sustainability improvement, as a percent of required expenditures

These measures are directly relevant to resource allocation decisions, so they are relatively easy for decision makers to understand and use. They can be tracked and updated using the same process as described above for the tradeoff analysis.

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CHAPTER 6. IMPLEMENTATION APPROACH

It is understood that the implementation plan for this methodology is still to be determined. In order to ensure widespread nationwide implementation, some or all of the following elements could be included in the plan:

- Extension of existing data standards to address condition of assets other than pavements and bridges.
- Extension of existing data standards to address resilience and site-based risk assessment.
- Development of a comprehensive all-asset multi-objective guidance manual to bring together, in one place, procedures for gathering and computing measures of condition, resilience, and performance, with the objective of supporting comprehensive transportation asset management.
- Development of additional rule-making to support implementation of the comprehensive manual, in particular to standardize the definitions of next-generation performance measures.
- Development of a prototype tradeoff analysis tool, provided as an Excel spreadsheet, that implements the methods described in this report and in the comprehensive guide.
- Modification of existing pavement and bridge management systems to produce the data format required by the tradeoff analysis tool.
- Research to fill in gaps in the current literature on performance consequences of TAM decisions.
- Development and execution of a communication strategy including articles, primers, and webinars to educate agency officials and their stakeholders on topics related to cross-asset tradeoff analysis.

Some of these activities could be undertaken by FHWA, while others might be appropriate for pooled-fund studies, NCHRP projects, or research administered by individual agencies. Cooperative efforts with management system developers would be needed in order to implement system linkages. While a few vendors have developed cross-asset databases and geographic information systems, these tools have not been extended to tradeoff analysis or decision support because of lack of standards and lack of understanding among developers and their customers. The implementation tasks suggested here could help to overcome these implementation barriers.

6.1 DATA REQUIREMENTS

The tradeoff analysis methodology described here has data requirements that are not much different from existing management systems and proposed federal performance rules. Since the cross-asset functionality does not exist in any of these existing systems and is outside the scope of those systems, it will be necessary to provide a way of extracting the necessary data from each system. In some cases, especially for assets other than pavements and bridges, the data may need to be assembled from multiple systems (e.g. maintenance management, geographic information, project management), and new software for long-term cost analysis and risk analysis may need to be developed.

6.1.1 ROAD SEGMENT DATA

A road segment inventory can provide the basic utilization and performance data required for most or all of the asset classes. Many of these items are found in the HPMS data set or a geographic information system.

- Demand and utilization – Functional class, traffic volume and growth rate, truck traffic, auto occupancy rate.
- Size – segment length and lane-miles.
- Speed – desired speed and congested speed.
- Detour route – length and speed.
- Cost – out-of-pocket cost if trips are mode-shifted

Performance forecast for each year up to TAM Plan horizon (unimproved base case):

- Crash count - Summed over all assets in the road segment. Road segment counts are developed from accident risk models and normalized to the statewide total, to ensure that they are consistent and not influenced by outlier data and normal year-to-year variation.
- Person-hours of excess travel time
  - Efficiency: Hours of lost time due to peak speed below desired
  - Reliability: Excess travel time due to unreliability (80th percentile minus 50th percentile time)
  - Congestion: Excess travel time during slow time slices
  - Resilience and function: Predicted delays and detours caused by the risk of adverse events, deteriorated conditions or functional deficiencies. This calculated for individual assets and then summed for the road segment.
- Excess travel distance due to detours – for bridge clearance and load rating deficiencies, this might affect only trucks; for risk analysis, all traffic might be affected by adverse events.

These measures would be separately computed for general traffic and for trucks, to enable levels of service and targets focused on freight mobility. The total estimated values for crashes, travel time, and travel distance are needed for benefit computations. They can be normalized, by dividing by VMT, for level of service standards, targets, and for tracking performance changes over time.

6.1.2 ASSET DATA

These data would normally come from an asset inventory, such as a pavement or bridge management system. For other asset classes, agencies may store these inventories in geographic information systems, maintenance management systems, or enterprise resource planning systems. All assets under the agency's jurisdiction should be included, even if they do not need any work, to enable the calculation of network-wide measures of condition, resilience, and performance.

Characteristics at the beginning of the program:

- Asset quantity - For asset weight in asset-specific performance measures (e.g. bridge deck area, pavement lane-mi)
- Asset condition – Based on the most recent condition survey. Pavement conditions may be stratified by distress type, and structure conditions by element and condition state. Condition may be summarized using an asset-specific condition index. For all asset classes the tradeoff analysis and proposed federal rules require a classification of condition as good, fair, or poor. In the longer-term this classification might rely on element or defect-level data and be calibrated to an economic concept such as feasibility of preservation work.
- Resilience – Classification of assets by resilience state, and/or a more precise resilience index such as a rockfall hazard rating system.

The following are needed for each forecast year up to the TAM Plan horizon (unimproved base case). Many of the models used in asset management are probabilistic, especially for deterioration and risk assessment. Therefore the conditions and performance losses are statistical expected value estimates.

- Condition - Probability of good condition and probability of poor condition
- Resilience - Probability of good resilience and probability of poor resilience
- Performance losses caused by asset condition, resilience, and deficiencies:
    - Modeled crash count
    - Person-hours of excess travel time
    - Truck-hours of excess travel time
    - Miles of detour travel
    - Dollars of excess travel cost
    - Dollars of environmental losses
    - Congestion losses – ultimately it would be valuable to be able to model the effects of volume/capacity ratio on excess travel time

Condition and resilience indexes are not necessarily needed for the tradeoff analysis but many agencies use them for communication of trends and for making comparisons among assets within an asset class.

6.1.3 PROJECT CANDIDATE DATA

These data would come from pavement and bridge management systems, or from specialized asset-level or network-level models developed for this purpose, such as those presented in Figure **16** and Figure **17**. Each record is an investment candidate corresponding to one record of the Investment Candidate file. Each record is characterized by references to one or more assets, a scope of work, and an implementation year.

For the benefit calculations, it is necessary to ensure that all applicable null alternatives are included in the data set. (See Table **10**). Project candidates may be filtered to remove investments that are outside the agency's jurisdiction, do not satisfy action criteria for any work, or that already received work during the past deferment period. Agencies typically plan and budget their routine maintenance work separately from programmed preservation or capital investments, so routine maintenance normally would not be included in the Investment Candidate File.

- Avoided long-term social cost - net present value of costs up to the long-term horizon, based on the management system life cycle cost and risk models where possible, or based on a generic model following the methodology in Figure **16** and Figure **17**.
    - Agency cost
    - Safety cost
    - Mobility cost
    - Environmental cost
- Estimated initial cost
    - Direct
    - Indirect
- The following are needed for each forecast year up to the TAM Plan horizon. Many of the models used in asset management are probabilistic, especially for deterioration, risk assessment, and treatment effectiveness. Therefore the conditions and performance losses are statistical expected value estimates.
    - Condition - Probability of good condition and probability of poor condition
    - Resilience - Probability of good resilience and probability of poor resilience
    - Avoided performance losses caused by asset condition, resilience, and deficiencies:
        - Modeled crash count
        - Person-hours of excess travel time
        - Truck-hours of excess travel time
        - Miles of detour travel
        - Dollars of excess travel cost

  - Dollars of environmental losses
  - Congestion losses – ultimately it would be valuable to be able to model the effects of volume/capacity ratio on excess travel time

6.1.4 GENERAL PARAMETERS

These system-wide parameters should be consistent with the parameters used in pavement and bridge management systems, and other planning tools used by the agency. In many cases these are default values to be used if individual assets do not have asset-specific or project-specific data.

- Default demand growth rate
- Default auto occupancy rate
- Default detour length
- Default desired speed by functional class
- Default congested speed by functional class
- Default detour route speed by functional class
- Default out-of-pocket cost per trip if mode-shifted, by functional class
- Default crashes per 100 million VMT
- Discount rate (for long-term cost analysis)
- Inflation rate (for funding requirements)
- Overhead rate (by treatment category)

6.2 SYSTEM REQUIREMENTS

The tradeoff analysis methodology discussed in this report provides the minimum capabilities required in order to support common TAM business processes across asset classes. Nearly all of the functionality described here can be found in some form in existing pavement and bridge management systems. However, these existing systems are often more detailed and complex than the basic cross-asset analysis, and typically use asset-specific performance measures that cannot readily be extended to the full range of transportation asset classes. The functionality of these systems is valuable for professionals who focus on specific asset classes, but the complexity creates difficulty for officials with cross-asset responsibilities.

The user group for cross-asset tradeoff analysis includes professionals focused on the economic and stakeholder perspectives in asset management. These users require a relatively simple interface to obtain useful information about pavement and bridge investment alternatives, information that is defined and structured in the same way across all asset classes. A significant communication gap and implementation barrier exists in agencies where this interface is not provided.

6.2.1 NEW CAPABILITIES

In order to overcome this communication gap, AASHTO's Transportation Asset Management Guide proposed the Investment Candidate File, containing essential information about proposed investments that is defined and formatted in a manner that applies equally well to all asset classes, and is compatible with existing pavement and bridge management systems. This file is meant to remain separate from existing management systems, so each system can innovate and evolve on its own time scale and its own body of research. The Investment Candidate File is meant to specialize in cross-asset decision support.

A valuable implementation task for the proposed methodology would be to implement the Investment Candidate File as a prototype software tool, and develop a basic set of calculations to execute the tradeoff analysis methodology. The tool would provide a basis for testing, validating, and refining the methodology; and could form the basis for customizations that individual agencies might create in order to apply the methodology to their own business needs. The following requirements would help the tool to achieve these purposes:

- Implement the tool as a spreadsheet file, incorporating ideas and methods from the variety of existing spreadsheet tools agencies are using already to serve parts of the framework. A well-developed spreadsheet tool would be highly customizable and adaptable to the unique requirements of each agency.
- Constrain the scope of the central tool to the generic tradeoff analysis presented in Figure **14** and Figure **18**, and Table **10**. Provide separate, supporting worksheets following the methods in Figure **16** and Figure **17** for asset-specific functionality. Agencies would use these supporting worksheets for asset classes other than pavements and bridges, and to supplement their management systems for any parts of the analysis not currently served by those systems.
- Worksheets focusing on each tradeoff analysis application in Table **10** would focus on the variables and network-level results, typically presented as a table and graph. Agencies can customize these to fit their distinct business needs.
- A separate spreadsheet file would be prepared as a data transfer format. Data provided in this format could be imported into the Investment Candidate File.
- The tool would be in the public domain and made freely available to agencies and developers from the FHWA web site.
- A Users Manual would be provided, including "how to" tutorials, reference information about each worksheet, and a technical description of the methodology.

The openness of the spreadsheet format and the constrained scope are very important to the success of the tool. It needs to be simple enough that agencies won't hesitate to try it, and won't be discouraged from spending the effort to master it. It needs to be as obvious as possible to each user what would need to be done to make it work for a specific agency. Agencies would be encouraged to build applications around the tool, such as geographic analysis, presentation tools, and interfaces with other systems. All of these enhancements would be outside the scope of the basic tradeoff analysis tool that FHWA would provide.

6.2.2 PAVEMENT AND BRIDGE MANAGEMENT SYSTEMS

One of the benefits of developing a prototype tradeoff analysis tool, is the ability to demonstrate a working model of an interface with existing pavement and bridge management systems. The data transfer worksheet would be modeled on the Investment Candidate File format presented in Table **2**, and would include all the data requirements listed in Section 6.1. Developers of commercial off the shelf management systems would be enlisted to develop export software for this interface.

The export software developed by each management system developer would be the property of that system's owner and would become a supported part of that firm's product. Because it is an open format, additional developers could begin to support it at any time, and agencies can develop their own interfaces as needed.

Since the tradeoff analysis tool is able to select from investment candidates provided by the management system, a potentially useful feature that management system developers may also want to provide is the ability to incorporate the selections back into the management system's own functionality. Not all pavement and bridge management systems have the ability to use this information, but some can provide a more detailed evaluation of the selected work, can group work candidates into projects, and can forecast element conditions based on the selected work.

This would enable the management system to provide additional value on top of the tradeoff tool's functionality.

6.2.3 OTHER ASSET CLASSES

As shown in Table **1**, a great many examples of inventories and condition surveys exist for assets other than pavements and bridges. Almost all of these are custom-developed systems, usually very simple. Some of these systems include analysis tools that cover part of the scope of Figure **16** and Figure **17**. The spreadsheet prototype would include generic worksheets to perform an asset-level analysis of treatment planning, long-term cost, and performance. Agencies can copy and customize these to fit their data and applications, and would be able to include as many of these as they need in the tradeoff analysis tool.

6.3 STANDARDIZATION REQUIREMENTS

FHWA rule-making in 23 CFR 490 promises to be extremely valuable to transportation agencies in standardizing commonly useful concepts of condition and performance. Other federal and AASHTO documents such as the HPMS Field Manual, the NBI Coding Guide, and the AASHTO Manual for Bridge Element Inspection are also valuable. There are many ways of describing and measuring performance, all of them useful in specified contexts, and many of them interchangeable. It can be difficult for agencies and developers to settle on a specific set of measures, so it is often the case that different systems use different measures to describe the same concept, thus introducing unnecessary incompatibilities and confusion. This is a major barrier to cross-asset tradeoff analysis.

On the other hand, once standards are in place, developers will support the standards in their analysis and reporting. Research and industry guidelines will support the standards with data collection and quality assurance methods. Common problems in using the standards will become more visible and more readily addressed by collective effort. Analysis tools using the standards are more easily shared among agencies. The proposed methodology will be most widely implemented if some additional standardization takes place. Topics for standardization include:

- Extension of existing data standards to address condition of assets other than pavements and bridges. For structural and geotechnical elements, guardrails, sidewalks, and other constructed assets, this could involve extension of the AASHTO Manual for Bridge Element Inspection. Portions of that extension could then be added to the federal NBI guidance if and when supported by legislation. Examples, developed by individual agencies, exist for all of these assets. Inspection procedures also exist for non-structural assets, especially for signs, traffic signals, pavement markings, and lighting.
- Extension of existing data standards to address resilience. While many agencies perform risk assessment, this activity has only recently been addressed in a comprehensive way in geotechnical asset management and in NCHRP Project 20-07(378) for bridges. The NCHRP work needed to draw on dozens of sources to compile all the ingredients necessary to assess the range of risks affecting bridge performance. There is a strong need for all-asset guidance drawing on the fragmented literature.
- FHWA has adopted a level of service approach for expressing performance targets in the 23 CFR 490 rules. There is not yet a documented basis for equivalence of the condition levels across asset classes: for example, a Poor pavement is not necessarily equivalent to a Poor bridge. Next-generation performance measures could use stakeholder surveys and economic concepts such as preservation feasibility to establish a more reliable cross-asset correspondence, which would enable the condition performance targets to be used in cross-asset tradeoff analysis.
- The concept of long-term social cost is uniquely able to unify all the major stakeholder concerns involved in cross-asset tradeoff analysis. Use of an economic concept for performance measurement opens the door to reliance on established economic principles to judge the quality of performance data and forecasts. It enables agencies to continuously improve their performance management, and provides an incentive to do so. Since economic concepts are uniformly scaled and additive, the framework facilitates gathering of performance estimates from a variety of sources while keeping them mutually compatible. Next-generation performance measures such as long-term agency cost, crash frequency estimates, travel time, travel distance, and travel cost have linear relationships with social cost and therefore require very little processing or interpretation

in order to be useful and understandable in tradeoff analysis. Standard, widely-used resources such as the AASHTO Red Book exist to monetize these measures. Future industry guidance could reinforce the role of long term social cost in optimizing the selection and design of projects, programs, and policies.

- TAM implementation would benefit from development of a comprehensive all-asset multi-objective guidance manual to bring together, in one place, procedures for gathering and computing measures of condition, resilience, and performance, with the objective of supporting comprehensive transportation asset management. The manual would address all of the business processes covered in this report in describing the methodology for estimating costs and benefits, and for tradeoff analysis. It would describe alternative approaches that fit TAM requirements, and would provide tips on tailoring the methodology to specific agencies.

Even with the increased standardization of asset condition, resilience, levels of service, and long-term social cost, there is still ample room for agency customization. Each agency has its own set of institutional constraints and processes that it must follow, its own policy emphases, its own set of site-based hazards, unique data collection capabilities, and unique treatments. Adoption of a standardized set of measures for cross-asset tradeoff analysis does not obviate the use of existing asset-specific measures for their existing purposes. Few agencies currently have a performance-based cross-asset tradeoff analysis capability, so the standards suggested here cover new ground and duplicate very little.

6.4 OPPORTUNITIES FOR FURTHER RESEARCH

By relying on research-based sources as much as possible, the proposed methodology maximizes objectivity and is able to be further improved as more research is completed. It is necessary to gather the research from a wide variety of sources, and rely on other studies where parts of this accumulation of relevant sources has already been done. Still, there are gaps in the methodology, where judgment may be necessary in the near-term until the necessary research and synthesis can be completed. Examples are:

- Models to forecast travel time reliability, related to congestion or day-to-day variation. Such models could be based on volume/capacity ratio, high crash probability, or other measurable factors.
- Estimation of the likelihood of service disruption for a variety of hazard scenarios, based on resilience characteristics of assets. The most significant of there are:
    - Crash rates as a function of skid resistance and pavement roughness;
    - Probability of over-height bridge collisions;
    - Crash rates as a function of rockfall characteristics;
    - Likelihood and consequence of intersection traffic signal failures;
    - Crash rates as a function of sign and pavement marking retroreflectivity;
    - Washouts as a function of culvert condition.

- Estimation of carbon dioxide emissions as a function of travel distance and speed, including the economic cost of such emissions.
- Estimation of noise impacts, particularly related to pavement and intersection characteristics, and including the economic impact of noise.
- Estimation of potential losses to water, agricultural, recreational, or cultural resources.
- Estimation of the energy consumption characteristics of assets, and the effect of various mitigation measures.
- Models of deterioration and costs for assets other than pavements and bridges.

In many of these cases, models exist in the literature but need to be adapted to data availability for TAM applications. The modularity of the methodology means that the individual research topics can be completed and added to the methodology separately on their own time frame, according to agency priorities.

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