State of Good Repair: Prioritizing the Rehabilitation and Replacement of Existing Capital Assets and Evaluating the Implications for Transit

DETAILS

124 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-25844-9 | DOI 10.17226/22732

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TRANSIT COOPERATIVE RESEARCH PROGRAM

TCRP REPORT 157

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Subscriber Categories
Public Transportation • Planning and Forecasting

Research sponsored by the Federal Transit Administration in cooperation with the Transit Development Corporation

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2012
www.TRB.org

TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transportation Association (APTA), Transportation 2000, also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA, the National Academies, acting through the Transportation Research Board (TRB); and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

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The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

TCRP REPORT 157

Project E-09
ISSN 1073-4872
ISBN 978-0-309-25844-9
Library of Congress Control Number 2012943634

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TRANSIT COOPERATIVE RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

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FOREWORD

By Dianne S. Schwager
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TCRP Report 157: State of Good Repair: Prioritizing the Rehabilitation and Replacement of Existing Capital Assets and Evaluating the Implications for Transit presents a framework for transit agencies to use for prioritizing capital asset rehabilitation and replacement decisions. By applying this framework, a decision maker can answer questions about asset rehabilitation and replacement investment decisions. The published report is accompanied by four Microsoft Excel models, which are available electronically via the TRB website. This report and the models will be a valuable resource for transit agencies and will be of interest to regional, state, and federal agencies that oversee, plan, or finance public transportation.

TCRP Report 157 presents the results of Transit Cooperative Research Program (TCRP) Project E-09 related to achieving a state of good repair for transit assets, focused specifically on approaches for evaluating and prioritizing rehabilitation and replacement investments in existing capital assets. The research reviewed existing state-of-good-repair practices in transit and other related industries. Based on the review, an evaluation was performed of the impacts and implications of different investment levels for rehabilitation and replacement of transit assets. The evaluation summarizes the positive and negative impacts of rehabilitation and replacement investment decisions and describes the performance measures used to quantify those impacts.

The research developed a framework for transit agencies to use for prioritization of capital asset rehabilitation and replacement decisions. The framework builds upon fundamental concepts involved in prioritizing asset rehabilitation and replacement decisions and provides a basic set of steps for transit agencies to follow. An analytical approach and set of spreadsheet tools were developed to support the framework. The tools address (a) how to evaluate rehabilitation and replacement actions for specific types of transit assets, and (b) how to prioritize candidate rehabilitation and replacement actions. The report presents a detailed example demonstrating application of the analytical approach and tools in support of the framework. Practitioners, researchers, and transit agencies can use the results of the research to better prioritize their investments in existing capital assets and better communicate the predicted impacts of a given set of rehabilitation and replacement investments.

This research is the first phase of a two-part research project. The next phase of the research will develop guidance for applying the approach developed through TCRP Project E-09. It includes transit agency pilots and a workshop for testing, refining, and communicating the implementation guidance for evaluating and prioritizing state-of-good-repair investments, as well as development of a set of web-based implementation support tools. This two-part project will help transit agencies evaluate and prioritize capital investments in transit assets for achieving a state of good repair.

CONTENTS

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

SUMMARY

U.S. public transportation agencies face an enormous set of challenges as they seek to preserve their existing capital assets. These agencies have a wide variety of assets to maintain and in many cases, these assets have aged to a point at or beyond the recommended interval for rehabilitation or replacement. Lacking adequate funds, these operators expect they will suffer significant reductions in system reliability, which may eventually result in restricted transit service. Asset preservation is an important concern not only for older, well-established transit operators, but also for newer and smaller transit systems. Transit agencies require improved tools to make the case for needed investments in their assets and to communicate the impacts of investing at a given level.

This report describes the results of a Transit Cooperative Research Program (TCRP) project related to achieving a state of good repair for transit assets, focused specifically on approaches for evaluating and prioritizing rehabilitation and replacement investments in existing capital assets. The effort involved reviewing existing state-of-good-repair practices in transit and other related industries. Based on the review, an evaluation was performed of the impacts and implications of different investment levels for rehabilitation and replacement of transit assets. The evaluation summarizes the positive and negative impacts of rehabilitation and replacement investment decisions, and describes the performance measures used to quantify those impacts.

An important element of the research was the development of a framework for transit agencies to use for prioritization of capital asset rehabilitation and replacement decisions. The framework builds upon a set of fundamental concepts and provides a basic set of steps for transit agencies to follow when evaluating and prioritizing rehabilitation and replacement investments. An analytical approach and set of spreadsheet tools were developed to support the framework. These address how to evaluate rehabilitation and replacement actions for specific types of transit assets, and how to prioritize candidate rehabilitation and replacement actions. A detailed example is provided that demonstrates application of the analytical approach and tools in support of the framework. Practitioners, researchers, and transit agencies can use the results of the research to better prioritize their investments in existing capital assets, and better communicate the predicted impacts of a given set of rehabilitation and replacement investments.

The results of the research are intended to be of immediate value for transit agencies. In addition, several areas have been identified through this effort where additional research may be merited to support further improvements in assessing and addressing state-of-good-repair concerns. These areas include the following:

- Implementation guidance for the framework, analytical approach, and tools developed through this research effort;

- Standards for asset data and condition assessment;
- Synthesis of models and approaches for track and track-related assets used in passenger and freight rail in the United States and abroad;
- Research on the relationship between asset condition and user impacts, such as delay;
- Improved high-level models for relating investment levels to performance;
- Quantification of transit agency prioritization strategies; and
- Guidance on applying asset management concepts to transit.

Further work in these areas would benefit transit agencies throughout the United States and abroad, extending the current research effort and providing transit agencies with additional advancements in the analysis of asset rehabilitation and replacement investments.

SECTION 1

Introduction

U.S. public transportation agencies face an enormous set of challenges as they seek to preserve their existing capital assets. These agencies have a wide variety of assets to maintain, as illustrated in the simplified taxonomy in Table 1-1. In many cases these assets have aged to a point at or beyond the recommended interval for rehabilitation or replacement. The Federal Transit Administration (FTA) *State of Good Repair Assessment* (*1*) documents this issue, calculating a backlog of more than $78 billion for state-of-good-repair needs for the U.S. transit industry. Without adequate funds, U.S. transit operators could eventually suffer significant reductions in system reliability that result in restricted transit service.

Asset preservation is an important concern not only for older, well-established transit operators, but also for newer and smaller transit systems. Since 2000, more than 20 new light rail, heavy rail, and commuter rail lines have entered revenue service. In the coming years these systems will need to plan for increased rehabilitation and replacement expenditures as their vehicles and infrastructure age. For smaller agencies focused on bus operations, the major assets that must be rehabilitated and replaced over time are buses, bus garages, and other fixed facilities. While buses are replaced on a more frequent cycle and are less costly per unit to maintain than rail vehicles and infrastructure, smaller transit agencies have fewer options when faced with insufficient capital funds. The increases in ridership seen in recent years by many transit systems are a mixed blessing with respect to addressing the backlog of rehabilitation and replacement needs for existing capital assets. Increased ridership is a benefit, but additional riders place additional demands on aging systems.

As transit agencies and other transportation organizations attempt to make the case for funds to rehabilitate or replace capital assets, they often encounter difficulty in effectively communicating the consequences of underinvestment, or conversely, the benefits of investing at a given level. It is one thing to explain the benefits of new service to the public and legislators—new service brings economic development, improved environmental sustainability, and a better quality of life for an area's residents. But what are the negative impacts of deferring the rehabilitation of a bus garage or replacement of deteriorated rail ties for a year—or perhaps for two or three?

This report describes the results of a Transit Cooperative Research Program (TCRP) project related to achieving state of good repair for transit assets, focused specifically on approaches for evaluating and prioritizing rehabilitation and replacement investments in existing capital assets. The research addressed a key set of research needs required to help transit agencies improve their analysis of state-of-good-repair needs. The objectives of the project were to:

- Develop a framework for public transportation organizations to use to prioritize rehabilitation and replacement of existing capital assets; and
- Identify methods for assessing the positive and negative consequences of varying investment levels on key indicators of public transportation service and performance.

The basic products of the research include a description of best practices in prioritization of rehabilitation and replacement decisions for capital assets, a framework for making prioritization decisions, and assessment methods and tools that transit agencies can use to predict performance based on different investment levels. Practitioners, researchers, and transit agency officials can use the results of the research to better prioritize their investments in existing capital assets, and better communicate the predicted impacts of a given set of rehabilitation and replacement investments. This report summarizes the results of the research effort and is organized as follows:

- **Section 2** presents findings from the review of existing practices in state-of-good-repair analysis. The review focused primarily on approaches for characterizing impacts and implications of rehabilitation and replacement investments in transit and other related industries.

Table 1-1. Simplified taxonomy of transit assets.

Category	Asset Type
Vehicles	Buses Cars Trucks Vans Heavy Rail Cars Light Rail Vehicles Locomotives Commuter Rail Cars Cable Cars Ferries Inclined Plan
Fixed Guideway	Track Special Track Work Third Rail Catenary Tunnels Elevated Structures Right-of-Way

Category	Asset Type
Facilities	Administration Maintenance Storage Maintenance Equipment
Systems	Train Control Electrification Communications Revenue Collection Utilities Drainage Ventilation
Stations	Station Structures Bus Shelters Elevators/Escalators Parking Garages/Lots Pedestrian Walkways Platforms Signage & Graphics

- **Section 3** discusses the impacts and implications of different investment levels for rehabilitation and replacement of transit assets. This section summarizes the positive and negative impacts of rehabilitation and replacement investment decisions, and describes the performance measures used to quantify those impacts.
- **Section 4** presents a framework for transit agencies to use for prioritization of capital asset rehabilitation and replacement decisions. The framework builds upon a set of fundamental concepts and provides a basic set of steps for transit agencies to follow when evaluating and prioritizing rehabilitation and replacement investments.
- **Section 5** details a set of tools and approaches for applying the framework to evaluate rehabilitation and replacement for specific types of transit assets. It describes an analytical approach for modeling vehicles and other asset types that deteriorate based on age or condition, as well as an approach for project prioritization. This section also describes a set of spreadsheet tools developed to support the approach, and follows a hypothetical example of the framework demonstrating the use of the tools and analytical approach.
- **Section 6** summarizes the results of the research.
- **Appendix A** provides additional details on the review summarized in Section 2.
- **Appendix B** is an annotated bibliography of the literature reviewed for the project, providing additional detail on the materials summarized in both Section 2 and Appendix A.
- **Appendix C** provides the interview guide used for the existing practice interviews.
- **Appendix D** provides additional details on existing practices collected through the interview process.
- **Appendix E** provides additional details on the analytical approach described in Section 5.
- **Appendix F** provides additional details on the example analysis described in Section 5.

SECTION 2

Review Findings

2.1 Review Approach

The initial step in the research effort was to perform a review of relevant literature on rehabilitation and replacement of existing capital assets published in the past decade. The review was intended to provide a comprehensive summary of approaches that have been used for prioritizing transit capital assets or that have been developed for managing other assets, but could be adapted for application to transit capital assets in the United States. It addressed materials related to transit state of good repair, asset and infrastructure management, management systems, best management practices and performance metrics, and other related topics. The review focused on transit industry examples, but included selected materials from related areas, including rail, highway asset management, and facilities. Appendix A contains additional information on the review approach, and Appendix B provides a detailed bibliography of the literature reviewed. Section 2.2 summarizes the results of the review.

The research team supplemented the literature review with a set of targeted interviews of transit agencies and other organizations. In some cases, the interviews were used to obtain information beyond that available in the literature. In other cases, the interviews helped provide an overview of existing and best practices in use in different organizations. Appendix A includes a list of the organizations interviewed, with the name of the primary contact at each organization, and focus area of each interview. Appendix C contains the interview guide, and Appendix D describes selected agency practices documented through the interviews.

Many of the materials profile the efforts of a particular agency to achieve a state of good repair, or summarize the experiences of multiple agencies in a particular area. In some instances, multiple presentations and papers describe different facets of the practices at the same agency. Appendix A provides a list of the case studies reviewed. The case studies are summarized below, to the extent that they describe specific methodologies, performance measures, or analytical approaches related to this report.

2.2 Review Results

The following subsections summarize the findings of the literature review and interviews. Section 2.2.1 describes basic approaches to transportation asset management, including guidance manuals, specifications, and other materials developed for transit, highways, and other infrastructure-intensive industries. Section 2.2.2 discusses efforts to define what constitutes a state of good repair, which has recently received much attention in the U.S. transit industry. Section 2.2.3 summarizes the findings on performance measures, focusing on research that characterizes impacts and implications of investments in rehabilitation and replacement of transit assets. Section 2.2.4 describes models and approaches related to the research described in this report.

2.2.1 Transportation Asset Management Methodologies

Asset management has received much interest in the U.S. transportation industry and internationally. Early efforts in the 1970s and 1980s focused on developing pavement, bridge, and maintenance management systems. By the 1990s, interest had increased in applying the techniques used for individual asset types to the full range of transportation assets. Though transit agencies face a unique set of challenges related to rehabilitating and replacing their existing assets, the broader transportation industry shares the basic problem of determining how best to preserve a set of existing assets. Indeed, this is a fundamental issue in transportation asset management.

Two international publications that provide general asset management guidance are of note in that they are intended for a broad spectrum of assets, including highways, transit infrastructure, facilities, and public utilities, and provide valuable information on best practices in asset management in a variety of industries. The National Asset Management Steering (NAMS) Group from Australia and New Zealand developed the *International Infrastructure Management Manual (IIMM),* as well as a suite of supporting documents (2). Also, the British Standards Institution (BSI) developed *Publicly Available Specification* (PAS) *55* for optimized management of physical assets (*3*). While IIMM and PAS 55 cover a wide range of assets, the underlying concepts presented in these documents are generally consistent with those of other guides specific to either transit or highway assets.

Transit Asset Management Methodologies

One area of focus for transit agencies has been to develop systems for capturing inventory and inspection data, which is a prerequisite for implementing an asset management approach. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) mandated that transit agencies adopt Public Transportation Management Systems (PTMS). Though they were subsequently dropped, the management system mandates served to propel efforts to develop PTMS. *TCRP Report 5: Guidelines for Development of Public Transportation Facilities and Equipment Management Systems,* published in 1995 provides an overview of a PTMS and provides guidance on implementing it for transit agencies, state departments of transportation (DOTs) and metropolitan planning organizations (MPOs) (*4*).

Recently, attention in transit asset management has shifted from implementing inventory and inspection data systems to using information from these systems to support an asset management approach. FTA published two documents that frame state of good repair in the context of transportation asset management, *National State of Good Repair Assessment* and *Rail Modernization Study (1, 5).* The report *Transit State of Good Repair: Beginning the Dialogue* summarizes the discussions of FTA's 2008 summit to begin the dialogue on state of good repair, which included descriptions of asset management principles for managing transit assets (*6*). The accompanying presentations from the summit provide additional details on the topics covered (*7*). The recent publication *Transit Asset Management Practices: A National and International Review* summarizes basic concepts of transportation asset management, reviews related practices in the transit industry, and compares representative best practices in the transit industry to the idealized practices described in the asset management literature (*8*). Another recent presentation by Laver summarizes state-of-good-repair concepts and relates these to asset management (*9*).

Highway Asset Management Methodologies

In the United States, much of the research pertaining to the development of general asset management guidance and methodologies has focused on highway assets. In 1997, the American Association of State Highway and Transportation Officials (AASHTO) formed a joint subcommittee on Transportation Asset Management, and in 1998 AASHTO adopted transportation asset management as a priority initiative. In 1999, the National Cooperative Highway Research Program (NCHRP) initiated Project 20-24(11) to develop the *AASHTO Transportation Asset Management Guide,* published in 2002 (*10*). More recently, AASHTO published a second volume to the *Transportation Asset Management Guide,* supplementing the material from the first volume and focusing on implementation (*11*).

AASHTO's guidance emphasizes that asset management should apply to the full set of physical assets in the transportation system and address a wide range of business processes. Furthermore, the basic objective of improving asset management is to improve decision making. AASHTO's 2006 definition, which is similar to definitions adopted by other organizations, is as follows:

> *Transportation asset management is a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their life cycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision making based upon quality information and well-defined objectives. (12)*

The 2011 AASHTO guide supplements this definition with a description of eight core concepts of effective asset management:

- Takes a network view;
- Aligns with strategic direction;
- Demonstrates leadership, which aligns the agency;
- Communicates with stakeholders;
- Makes data-driven, informed decisions;
- Integrates agency programs and budgets;
- Monitors outcomes; and
- Focuses on continuous improvement.

Together, the two AASHTO guides extensively cover the underlying concepts in transportation asset management, and the 2011 guide provides best practices in more than a dozen transportation agencies in the United States and internationally. Several other NCHRP reports detail specific topics in transportation asset management, and thus serve to complement the AASHTO guides. *NCHRP Report 222* provides guidance in establishing maintenance quality assurance programs, including a definition of levels of service for characterizing maintenance, and information on implementing sampling to measure conditions (*13*). *NCHRP Report 446* and *NCHRP Report 551* describe the use of performance measures in transportation planning and asset management (*14, 15*). Performance management is an important aspect of asset management, but also the subject of much interest more broadly in the transportation community. *NCHRP Report 545* describes analytical tools for asset management, providing a thorough review of existing analytical tools and gaps in existing tool capabilities as of 2005 (*16*). *NCHRP Report 632* discusses how to implement best practices in asset management to the Interstate Highway System (*17*). This report incorporates a review of available asset management data, systems and tools for highway assets.

Review of Findings

The review of materials on asset management methodologies and guidance yielded the following findings pertaining to this research:

- The basic transportation and infrastructure asset management methodologies developed domestically and internationally, though largely developed to support managing highway assets (particularly pavements and bridges), are highly applicable to managing transit assets. Recent asset management guidance documents, particularly the IIMM and PAS 55, tend to emphasize basic concepts underlying management of all physical assets, and incorporate best practices from industries including highways, transit, facilities, and public utilities.
- The asset management methodologies and guidance documents do not typically recommend specific approaches for characterizing implications of a given investment level in rehabilitation and replacement of transit assets.
- A fundamental tenet of the asset management methodologies and guidance documents reviewed is that investment decisions should be based on quality data. An important step in implementing an asset management approach is to collect accurate and comprehensive inventory and inspection data on an organization's physical assets. Data should extend beyond the basics—such as the date the asset was constructed or purchased—and include the level of use and condition of the asset to predict its current and future performance.
- Measuring and reporting performance is an important aspect of asset management. Many of the implementation examples in the literature describe efforts to implement performance measurement, tracking and reporting approaches. Typically these efforts involve establishing a set of performance measures for an organization's existing assets, establishing targets for those measures, and then reporting on progress towards the organization's targets.
- The literature reviewed, particularly the AASHTO and NCHRP guides and reports, emphasizes that high-level investment decisions should encompass all asset and investment categories, consider trade-offs between different objectives during resource allocation, and balance competing needs given an organization's policies, goals, and objectives. However, these guides and reports provide little information on how to prioritize investments given a limited budget allocation. In the case of highways, rehabilitation and replacement investments are prioritized within each asset/investment category, except for major projects.

2.2.2 State-of-Good-Repair Problem Definition

Much of the recent literature on rehabilitation and replacement of transit capital assets discusses what constitutes a state of good repair for a particular transit agency or for the nation. The materials from the FTA State of Good Repair Summit detail definitions of the term state of good repair used in several agencies (*6*). The definitions presented in that document are shown in Table 2-1.

Other recent papers provide additional discussion of the different approaches to defining state of good repair (*18, 19*). The TCRP State of Good Repair International Study Mission conducted in 2010 examined definitions used by six agencies in Europe (*20*). The presentation "International Transit Studies: State of Good Repair Definition and Measurement" summarizes definitions used by agencies in France, Germany, Norway and the United Kingdom visited as part of the study mission (*21*). Other presentations from the FTA State of Good Repair Roundtables provide additional information on experiences of specific U.S. agencies, including how these agencies define state of good repair. These case studies are listed in Appendix A.

FTA has prepared several recent calculations of investments required for achieving a state of good repair at a national level. FTA estimates transit investment needs on a biennial basis, publishing its results in the Conditions & Performance Report to Congress (termed the "C&P Report") prepared jointly with the Federal Highway Administration (FHWA). The most recent C&P Report was published in 2009 (*22*). FTA has prepared separate estimates of the investments required to achieve a state of good repair for the U.S. transit industry as a whole (*1*), and for the seven largest U.S. rail systems (*5*). All of these studies have been performed using FTA's Transit Economics Requirements Model (TERM), described further in Section 2.2.4. The FTA publications are notable for a variety of reasons, including the effort to establish consistent definitions for transit rehabilitation and replacement needs for U.S.

Table 2-1. Alternative definitions of state of good repair (SGR).

Agency	*Definition*
Chicago Transit Authority (CTA) Illinois	CTA defines SGR primarily in terms of standards: Rail lines should be free of slow zones and have reliable signals. Buses should be rehabbed at six years and replaced at 12 years. Rail cars should be rehabbed at quarter- and half-life intervals and replaced at 25 years. Maintenance facilities should be replaced at 40 years (70 years if rehabbed).
Cleveland Regional Transit Authority (RTA) Ohio	State of good repair projects are those needed to bring the system to a consistent, high quality condition system-wide.
Massachusetts Bay Transportation Authority (MBTA) Massachusetts	A state of good repair standard [is where] all capital assets are functioning at their ideal capacity within their design life.
New Jersey Transit (NJ Transit) New Jersey	State of good repair is achieved when the infrastructure components are replaced on a schedule consistent with their life expectancy.
New York City Transit (NYCT) New York	Investments that address deteriorated conditions and make up for past disinvestment.
Southeastern Pennsylvania Transportation Authority (SEPTA) Pennsylvania	An asset or system is in a state of good repair when no backlog of needs exists and no component is beyond its useful life. State of good repair projects correct past deferred maintenance, or replace capital assets that have exceeded their useful life.

Source: FTA (*6*)

transit operators. The TERM model rates asset condition on a scale from one (poor) to five (excellent). Existing condition and future deterioration on this scale is predicted strictly based on asset age. An asset is deemed to be in a state of good repair if its condition rating is 2.5 or greater, and in need of replacement if its rating is less than 2.5.

Notwithstanding these FTA efforts, no specific program exists at the national level for helping to achieve a state of good repair for U.S. transit assets. However, several recent presentations describe different proposals for and considerations in formalizing state-of-good-repair definitions and funding in order to promote transit state-of-good-repair concepts at a national level. Libberton summarizes FTA's recent efforts to "make a federal case out of state of good repair," including FTA's efforts to sponsor roundtables, discussion, and training related to this topic (*23*). Waaramaa and Jaffe outline the activities of the FTA – Industry SGR Working Group, which has considered how to define and measure what constitutes a state of good repair (*24*). Tuccillo and McMillan each describe different possible approaches for future funding of state-of-good-repair projects in the next transportation reauthorization legislation (*25, 26*). Finally, James proposes three alternative models to define state of good repair for a federal program (*27*). These definitions are particularly useful in that they encompass many of the concepts described in the other definitions covered in the review (see Figure 2-1).

The review of materials on state-of-good-repair definitions and estimates yielded the following findings pertinent to this research:

- Transit agencies in the United States and abroad have established a number of different definitions of the term "state of good repair" and no consensus exists on the definition. A straightforward approach is to define the state of good repair as the point at which all of a transit agency's assets are in good condition, and several of the definitions described above reflect this approach. However, the reality is that even in the ideal situation, assets age and deteriorate, and in a steady state condition, a transit agency will always have some assets in need of rehabilitation and replacement. Most definitions implicitly acknowledge this fact, and essentially define the state of good repair as the point where transit agency policies (formal or informal) are being followed for maintenance, rehabilitation, and replacement of existing transit assets. However, transit agencies have different ways of expressing these policies, and thus different definitions for the term.
- In the absence of a national consensus on the definition of a state of good repair, the de facto definition is that used by FTA for its reports to Congress on transit investment needs and incorporated in TERM. Based on TERM, an asset is in a state of good repair if its condition rating is 2.5 or greater. This threshold value can be equated to a specific age, which is a function of asset type.
- The literature on defining a state of good repair is related to this research report in that it addresses transit asset rehabilitation and replacement, raises issues of how asset performance is measured, and concerns modeling investment needs. The discussion of the alternative definitions is pertinent to the question of what investments are required in transit assets. However, the definitions of "state of good repair" are secondary to the focus of this report, which is concerned with how to prioritize rehabilitation and replacement investments and what the impacts and implications of a given investment level might be. The literature on state-of-good-repair definitions generally does not address these topics, except as noted in the following subsections.

Model 1

A transit system is in a state of good repair when:

- The transit agency possesses and maintains a comprehensive list of its capital assets and rolling stock.
- The transit agency possesses an asset management plan which is integrated into the management processes and practices of the agency.
- A set percentage of the transit agency's assets are within their articulated useful life and remaining assets are performing at their designed function.

Model 2

A transit system is in a state of good repair when:

- System components are properly maintained or replaced, in accordance with:
  - The owner's approved operation and maintenance (O&M) procedures and schedules, or
  - The original equipment manufacturers' (OEM) recommended criteria when owner's procedures do not exist, or
  - Industry standards when the above are not available.
- The system satisfactorily performs its intended design function.

Model 3

A transit system is in a state of good repair if it exhibits the following characteristics:

- Safety—Transit infrastructure and vehicles are well-maintained and replaced before their condition deteriorates to the point of presenting a safety risk.
- Quality Transit—Infrastructure and vehicles meet customer expectations for comport and reliability.

Source: James (*27*)

Figure 2-1. Models for defining state of good repair for a federal program.

2.2.3 Performance Measures for Transit Assets

The review included a number of reports, papers, and documents related to performance management. As noted above, establishing a performance management program is viewed as an important aspect of implementing an asset management approach, and many of the materials related to implementing an asset management approach described in Section 2.2.1 address this topic. *NCHRP Report 551* (*15*) is noteworthy because it focuses specifically upon performance measures for asset management. This report lists examples of performance measures, and includes guidance for establishing performance measures and targets for asset management. However, like many of the asset management references included in the review, this report focuses primarily on performance measures for highway assets, such as roads and bridges. The case studies of Washington State DOT (WSDOT) and New Jersey DOT (NJDOT) provided in Appendix D describe how these organizations have established performance measures for their assets, and are representative of best practices used for performance management for highways.

Regarding performance measures for transit, the definitive guide is *TCRP Report 88: A Guidebook for Developing a Transit Performance-Measurement System* (*28*). This report presents a categorization for transit performance measures, provides an extensive catalog of performance measures, and details a set of case studies illustrating implementation of performance management programs. Most of the performance measures discussed in this document relate to other aspects of transit performance that may be impacted by, but are not a direct result of, asset conditions and maintenance. For example, on-time performance is primarily viewed as an operations issue, though excessive breakdowns or slow orders will obviously impact this measure. However, measures in the service delivery, safety and security, and maintenance and construction categories such as reliability, comfort, vehicle accident and road calls rate are directly related to asset conditions, and may be relevant for consideration in developing tools and approaches for characterizing impacts of alternative investment levels for transit assets.

TCRP Report 141, published in 2010, describes a methodology for peer comparisons and performance measurement (*29*). This guide lists measures in nine categories to be used to support peer-to-peer comparisons:

- Cost-efficiency;
- Cost-effectiveness;
- Productivity;
- Service utilization;
- Resource utilization;
- Labor administration;
- Maintenance administration;

- Perceived service quality; and
- Safety and security.

A number of U.S. transit agencies provide performance data online. In many cases the information available online is a subset of that reported to the National Transit Database (NTD). However, particularly for larger rail operators, the available data often include measures related to the state of repair of the system beyond that available through the NTD. Appendix D describes the performance measures published by NYCT, which include measures of equipment availability and wait times. The research team reviewed the websites of a number of U.S. transit agencies. The review indicated that agencies such as the MBTA, CTA and San Francisco Bay Area Transit District (BART) provide additional information on the conditions and performance of their systems beyond that available through the NTD (*30, 31, 32*).

Several other references included in the review survey performance measures used for transit asset management in the United States and internationally. The presentation "International Transit Studies: State of Good Repair Definition and Measurement" (*21*) reviews performance measures used at transit agencies in France, Germany, Norway and the United Kingdom. *TCRP Research Results Digest 95* details the results of the Spring 2009 mission of the International Transit Studies Program to review performance measurement approaches at organizations in Hong Kong, Kuala Lumpur, Singapore, and Taipei (*33*). FTA's review of transit asset management practice discusses performance measures used at organizations in the United States and internationally (*8*).

Many of the materials included in the review discuss measures used by specific transit agencies, or for specific analyses. Table 2-2 summarizes different measures related to transit asset conditions and performance identified through the review and interviews. The measures are organized by general category and type of measure, with specific examples of each type. For common measures—such as mean time between failures (MTBF), mean distance between failures (MDBF), and asset age—the table provides examples that are illustrative rather than exhaustive in nature. It is notable that there are relatively few measures related to environmental issues. Achieving sustainability and improving the environment are important objectives for many agencies, but in this area it can be difficult to tie system-level performance to asset-specific measures. One approach to characterizing environmental performance is to track which vehicles in a transit agency's fleet meet specified emissions or other standards, as noted in the table. Another approach is to characterize carbon dioxide (CO_2) emissions per vehicle mile (*34*).

A small number of papers and presentations in the review focus on relating asset conditions to broad measures of safety and performance and/or defining new performance measures to better characterize transit asset conditions. Flanigon discusses the increase in accidents observed in passenger rail from 2003 to 2008, and discusses the relationship between deferred maintenance and safety (*37*). Arkin discusses the relationship between system reliability and preventive maintenance and the negative impacts of allowing transit components to fail, concluding that Reliability, Availability, Maintainability, and Safety (RAMS) specifications should be included in contract specifications to minimize these impacts (*38*). Waaramaa and Jaffe's presentation presents a possible new measure of asset condition, combining measures of asset age, condition, performance, and level of maintenance on a five-point scale similar to that used for TERM (*24*).

The review yielded the following findings pertaining to performance measures characterizing asset conditions and/or state of repair.

- The most common measures for characterizing impacts of transit asset rehabilitation and replacement investments include: the cost of achieving a state of good repair or backlog of investment needs; several variants of asset age; and average asset condition on the TERM five-point scale (which in TERM is derived from age data). These measures have the advantage of being readily derivable from available data, but provide little insight into customer impacts resulting from a given investment level.
- Other common measures associated with asset conditions and/or state of repair include failure rates (mean time/distance between failures), numbers of failures or defects, and a number of measures of asset availability (e.g., spare ratio, percent of assets in service, percent of system under slow orders).
- London Underground (LU) is notable in that it uses measures intended to directly relate asset conditions to performance as perceived by the customer. LU uses journey time as an indication of asset capability, and lost customer hours (LCH) to characterize asset reliability.

2.2.4 Analytical Approaches

Analytical approaches for assessing and prioritizing asset rehabilitation and replacement are central to this research effort. The review considered analytical approaches used across the transportation industry and other related industries that could be applied to transit assets, as well as the models and approaches implemented within the transit industry.

Analytical Approaches for Transit Assets

Several approaches have been implemented in the United States for analyzing implications and/or prioritizing transit

Table 2-2. Representative measures of transit asset conditions and performance.

Category	Type	Measure	Example Application
Asset Condition	Age	Average Fleet Age	*TCRP Report 141* (*29*)
		Average Age of Assets as Percent of Their Useful Life (AAAPUL)	Metropolitan Transportation Commission (MTC) (Appendix D)
		Remaining Useful Life	MBTA (Appendix D)
	Condition	Percent of Assets in a State of Good Repair	FTA (*1*, *5*, *22*)
		Condition Rating	FTA (*1*, *5*, *22*)
		Percent of Assets Eligible for Replacement	MTC (Appendix D)
		Percent of Vehicles with Functioning Climate Control Systems	NYCT (*28*)
Cost	Investment Needs	Estimated Cost to Achieve Target Condition Level or Eliminate Deficiencies	FTA (*1*, *5*, *22*)
	Maintenance Cost	Average Annual Maintenance Cost Per Vehicle Operated in Maximum Service	*TCRP Report 141* (*29*)
		Maintenance Full Time Equivalents (FTE) per Vehicle Operated in Maximum Service	
		Non-Vehicle Maintenance Cost/Track Mile	
		Maintenance Cost per Revenue Mile/Hour	
Availability/ Capability	Accessibility (Capability to Meet Accessibility Commitments)	Percent of Trips/Vehicles Wheelchair Accessible	Metropolitan Transit Authority of Harris County (Houston METRO) (*28*)
	Sustainability (Capability to Meet Environmental Commitments)	Percent of Fleet Meeting Emissions Standards	Mass Transit Railway Corporation Limited of Hong Kong (Hong Kong MTRCL) (*33*)
	Availability of Safety Equipment	Percent of Vehicles with Specified Safety Devices	Los Angeles County Metropolitan Transportation Authority (*28*)

(continued on next page)

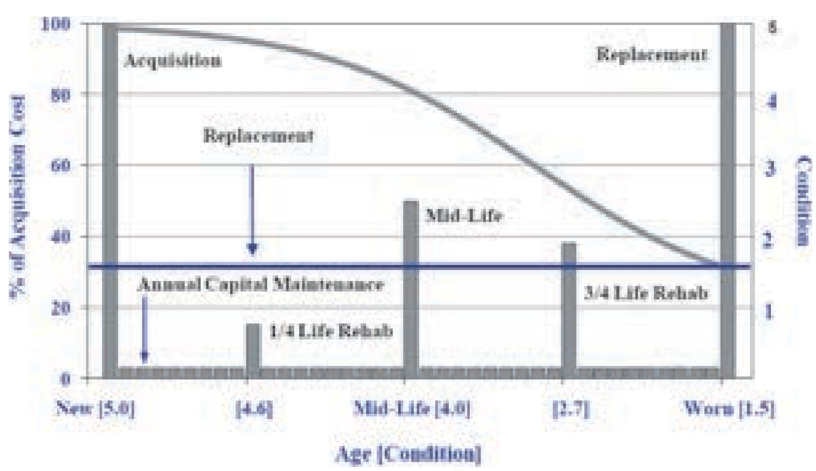
Table 2-2. (Continued).

Category	Type	Measure	Example Application
	Quantity Unavailable for Intended Use	Percent of Slow Zone Mileage	CTA (*31*)
		Minutes of Impact of Speed Restrictions	MBTA (*30*)
		Percent Asset Quantity Out of Service Due to Deteriorated Condition	*NCHRP Report 551* (*15*)
		Average Number of Stations with Out-of-Service Elevators/Escalators	BART (*32*), Hong Kong MTRCL (*35*)
		Actual Number of Departures as Percent of Scheduled Number of Departures During Peak Hours	Hong Kong MTRCL (*33*)
		Automated Fare Collector Gate Availability	BART (*32*)
		Percent of Time Ticket Machines in Service	NYCT (*28*), BART (*32*)
	Travel Time	Average Journey Travel Time	London Underground (Appendix D)
	Spare Ratio	Ratio of Spare Vehicle Quantity to Fleet Size	*TCRP Report 141* (*29*)
		Ratio of Number of Vehicles Available for Service to Number of Vehicles Required for Peak Service	MBTA (*30*)
		Percent of Licensed Fleet that is Actually on the Road	Hong Kong MTRCL (*33*)
		Average Spare Ratio vs. Scheduled Spare Ratio	*TCRP Report 88* (*28*)
Reliability	Failure Rate	Mean Time/Distance Between Failures	*TCRP Report 141* (*29*)
		Percent of Lost/Dropped Trips	MBTA (*30*), Hong Kong MTRCL (*33*)
		Number of Bus Defects Per Vehicle Per Year	Hong Kong MTRCL (*33*)
		Unscheduled Door Openings per Million Car Miles	BART (*32*)
		Wheelchair Lift Failure Rate	NYCT (*28*)
	Number of Failures	Number of Road Calls	San Francisco Municipal Transportation Administration (San Francisco MUNI) (*28*)
		Number of Subway Derailments	NYCT (Appendix D)
		Number of Fires	NYCT (Appendix D)

Table 2-2. (Continued).

Category	Type	Measure	Example Application
	Delay to Customers	Lost Customer Hours	London Underground (Appendix D)
		Subway Wait Assessment	NYCT (Appendix D)
		Delays per 100 Trips	BART (*32*)
		Actual Number of Departures as Percent of Scheduled Number of Departures During Peak Hours	Hong Kong MTRCL (*28*)
Service Quality	Passenger Comfort and Convenience	Ambience Score	London Underground (Appendix D)
		Cleanliness Score	CTA (*31*), BART (*32*), Foothills Transit (*36*), Hong Kong MTRCL (*33*),
		Comfortable Temperature Score	BART (*32*)
	Ride Quality	Acceleration/Jerk Levels	Amtrak (Appendix D)

asset rehabilitation and replacement actions. As noted previously, FTA uses TERM for analyzing transit rehabilitation and replacement needs. The *TERM User's Guide* details the modeling approach used by the system (*39*). TERM uses data from the NTD and other sources to determine the existing inventory of transit assets and the age of those assets. TERM uses asset age as a proxy for asset condition. For each asset type a relationship between asset age and condition is defined, with condition measured on a five-point scale. TERM predicts asset replacement needs for each year by determining which assets will reach a condition rating less than 2.5. Also, depending on the asset, maintenance costs may be modeled as occurring annually, and asset rehabilitation actions may be modeled at half or quarter-life intervals. No change in condition is modeled as a result of maintenance or rehabilitation actions. Figure 2-2, reproduced from the *TERM User's Guide,* illustrates a representative set of models for asset deterioration and action costs. The TERM models result in predictions of maintenance, rehabilitation, and replacement costs over time by asset type, as well as average asset conditions. To adjust the amount of expenditures, or the average condition achieved, one can adjust the threshold at which assets are replaced



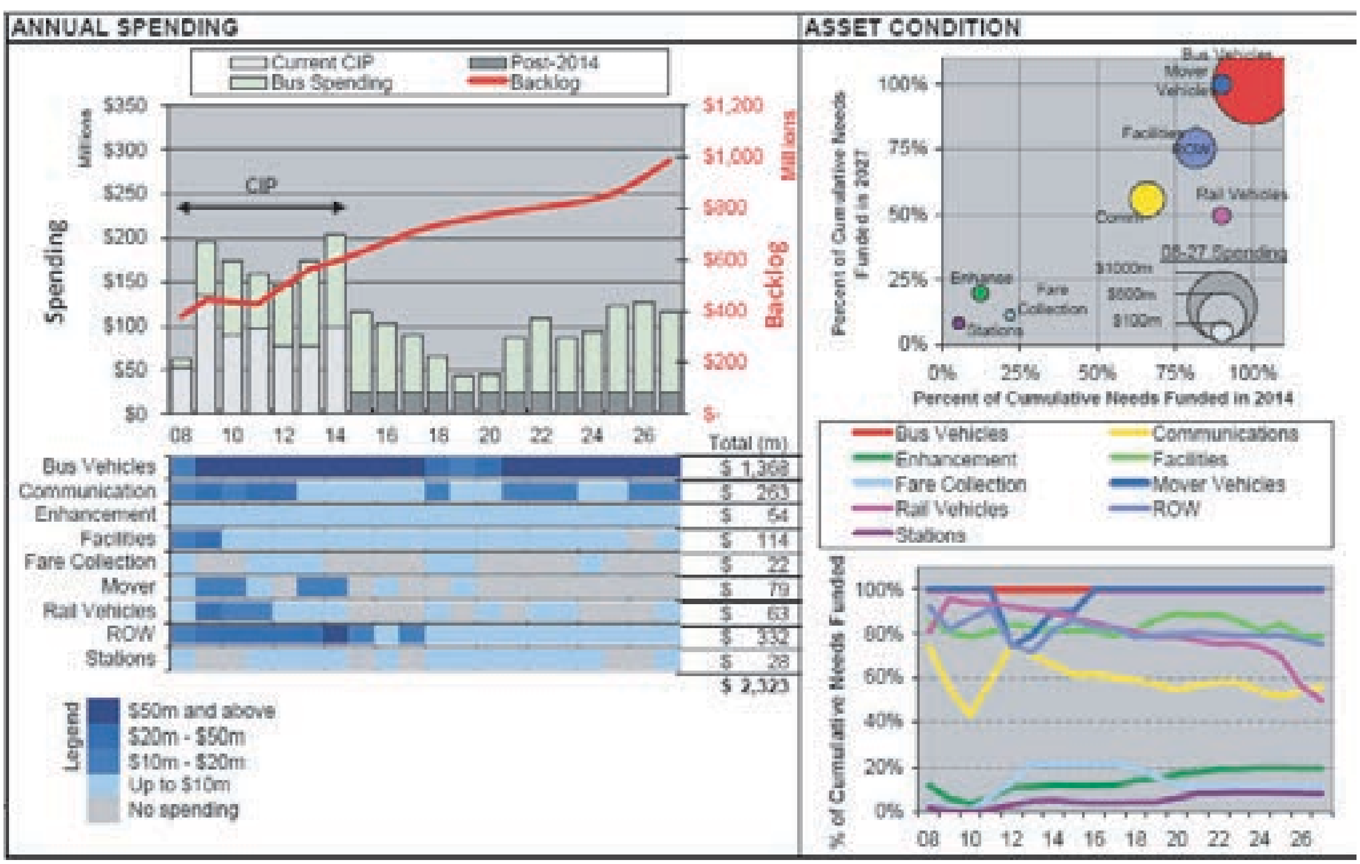
Source: Booz Allen Hamilton (*39*)

Figure 2-2. Example TERM asset model.

by shifting the threshold greater or less than the default of 2.5. In 2011, FTA released TERM Lite, a version of TERM intended for transit agency use.

Other organizations have used modeling approaches based on or similar to that in TERM. The Metropolitan Transportation Commission (MTC) uses the Regional Transit Capital Inventory (RTCI) database to model asset replacement needs for Bay area transit agencies. This model is described by Tepke (*40*) and in Appendix D. As in the case of TERM, the RTCI assumes a fixed set of asset lives (specified in years rather than a condition threshold), and models replacement costs expected over time as assets reach and are replaced at the end of their useful life. Key measures generated by the model include asset replacement needs and the predicted Average Age of Assets as a Percentage of their Useful Life (AAAPUL). Giuffre et al. describes the Virginia Department of Rail & Public Transit (DRPT) Program Guidance and Grant Evaluation System (PROGGRES) used to analyze transit investment needs for DRPT, which also models investment needs based on fixed asset life assumptions (*41*). Based on the interview results, a number of other agencies estimate asset rehabilitation and replacement needs in a similar manner, using information on the age of their existing assets and the estimated life for those assets expressed in years.

Another basic approach described in the literature is the MBTA State of Good Repair (SGR) database, documented in Appendix D and in a number of references (*42, 43, 44, 45, 46*). This model is notable in that it both estimates asset rehabilitation and replacement needs and prioritizes allocation of funds to rehabilitation and replacement needs given a budget constraint. To use the database, the MBTA defines candidate asset rehabilitation and replacement projects. For each candidate, three basic measures are quantified: the age of the asset as a percent of its useful life (used as a proxy for service quality), operational impact of the candidate project (yes/no value), and cost effectiveness of the project (ridership impacted divided by the cost of the action). The system then simulates candidate projects over time given a budget constraint, prioritizing what projects to perform given user-specified weights on the service quality, operational impact, and cost effectiveness factors. Though the system was initially implemented for the MBTA, the system's developer, AECOM, has used the system for analyzing investment needs for other agencies, such as San Francisco MUNI (*47*). Figure 2-3 shows



Source: Peskin and Antos (*44*)

Figure 2-3. Example results from the MBTA SGR database.

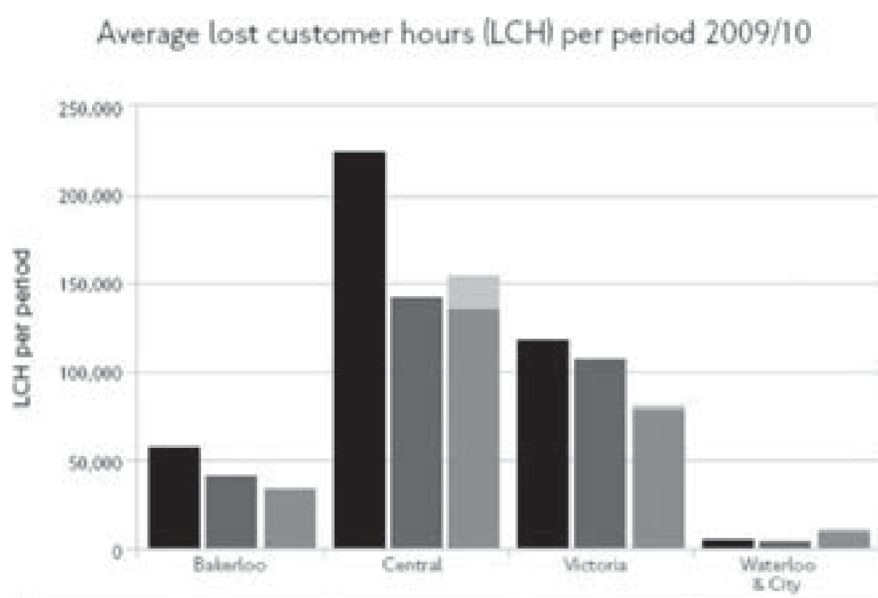
example results generated from the MBTA SGR database. In this example, the left panel shows anticipated spending and the backlog of SGR needs, as well the extent of needs by asset type. The right panel shows the cumulative percent of needs funded by year and asset type.

A notable model for predicting impacts and implications of asset rehabilitation and replacement is LU's model for predicting LCH as a result of different types of systems interruptions and failures. LU's approach is described in Appendix D and results from the modeling of LCH are presented in LU's performance reports, such as (*48*). Figure 2-4 shows example LCH results from a recent performance report that illustrates benchmark, projected, and estimated actual LCH values for four lines. Although the details of the LCH projections have not been published in the literature, the model is significant in that it relates customer impacts to asset maintenance and provides a means for prioritizing investments across asset types.

The analytical approaches described above are used for investment analysis and reporting, but are not used directly for prioritizing investments. Both MTC and MBTA have established separate prioritization approaches that prioritize asset rehabilitation needs based on a variety of factors. These approaches are described in Appendix D. Results from MTC's RTCI and MBTA SGR Database help inform prioritization decisions. MBTA uses the results as an explicit factor in the prioritization process, but in both cases, other factors are considered as well. Several transit agencies, including San Francisco Municipal Railway (MUNI), are exploring a capital planning and budgeting software tool developed by Decision Lens to help quantify the project prioritization criteria and determine weights on different criteria through a group decision-making process (*49*). San Francisco MUNI is testing a model that combines results from the MBTA SGR Database and Decision Lens (*47*). A number of the project scoring approaches have been implemented for transit decisions, but as in the case of highways these are often used for prioritizing major expansion projects rather than asset rehabilitation and replacement investments. For instance, Berechman and Paaswell describe a method to evaluate high capital cost transportation projects for New York City considering life cycle costs, as well as changes in ridership, travel times, levels of commercial, residential and retail development, job levels, incomes, and tax revenues (*50*).

Other analytical approaches used for individual transit agencies or research efforts identified through the review include:

- Khasnabis et al. describe a set of models developed for Michigan DOT for allocating capital funds to bus fleet



	Bakerloo	Central	Victoria	Waterloo & City
Contract Benchmark	56,600	223,800	117,000	4,800
Bid Projection	40,889	141,663	105,978	3,382
Achieved (Agreed)	33,543	135,593	79,833	10,193
Achieved (Abeyance)	572	17912	524	41

Source: London Underground Limited (*48*)

Figure 2-4. London Underground Bakerloo-Central-Victoria-Waterloo LCH projections.

replacement, rehabilitation, and remanufacture maximizing remaining fleet life (*51*).

- Keles and Hartman formulate an approach for determining the optimal schedule for bus replacement considering replacement timing and the selection between suppliers minimizing discounted cash flow (*52*).
- Li et al. describe application for prioritizing bus replacement using an Ordered Probit Model (OPM) that links maintenance spending, vehicle age, vehicle mileage, and condition (*53*).
- Anderson and Davenport describe a Rural Transit Asset Management System developed for Alabama DOT that simulates vehicle replacements predicting vehicle condition based on age, total miles traveled, annual mileage on unpaved roads, presence of wheel chair lift equipment, and percentage of population that is over 65 years old (*54*).
- The report *Useful Life of Transit Buses and Vans* prepared for FTA by Booz Allen Hamilton Inc. described a comprehensive research effort to evaluate the FTA minimum service-life requirements for buses. The report includes an engineering analysis of the life cycle costs of bus operations (*55*).
- Scarf et al. apply a modified version of a two-cycle model for use in modeling replacement of escalators for the Mass Transit Railway Corporation Limited (MTRCL) of Hong Kong considering maintenance costs and the cost to the transit agency and users in the event of an asset failure (*35*).

Analytical Approaches for Railroads, Facilities and Utilities

Of the general guidance materials described in Section 2.2.1, IIMM is notable for its coverage of international examples and related industries (*2*). To supplement this information, an overview of asset management practices in the railroad industry was obtained by interviewing staff at Amtrak and reviewing two recent postaudits of industry research efforts performed for the Association of American Railroads (AAR) (*56, 57*). In the 1980s and 1990s, the U.S. railroad industry recovered from a long period of deferred maintenance, and recently has realized significant benefits from improved asset maintenance practices and increased productivity. The railroad industry is focused on using condition-based approaches for rehabilitation and replacement of rail and other assets. They are guided by frequently collected and detailed data on defect or failure rates and accumulated tonnage, and involve determination of the threshold values at which rehabilitation or replacement is shown to be most cost effective (e.g., for detector readings used for monitoring vehicle conditions and defect and wear limits for track).

The review did not yield examples of analytical models being used to support prioritization of rehabilitation and replacement project-level investments for railroads across asset types. In contrast to practices at many U.S. transit agencies, budgets for Class I railroads are typically established by broad categories (e.g., for vehicle replacement or rail relaying), and systematic project-level prioritization approaches are less important for supporting the business process. Where there are interactions between different types of asset types, the engineering and logistical challenges of scoping and delivering projects on the railroads defy straightforward prioritization approaches. For example, in the case of Amtrak, a major state-of-good-repair issue is that of replacing cracked concrete ties on the Northeast Corridor. Needs for tie replacement are determined through visual inspections as described in Appendix D. Replacement of individual ties is performed as a maintenance activity, but wholesale tie replacement must be planned far in advance. Closing a portion of the Northeast Corridor for wholesale tie replacement can pose major logistical challenges and must be carefully coordinated with other railroads and commuter rail operators. Thus, Amtrak schedules the operations of its track crews and track laying machine (TLM) far in advance and attempts to address whatever asset rehabilitation and replacement needs it can—including rails, ties, and ballast—when closing a portion of the Northeast Corridor.

For other infrastructure-intensive industries outside of transportation, common approaches include analyzing needs based on asset age and/or condition with thresholds defined for the service life of the assets. Grussing et al. present a framework for optimizing investments for facilities using condition indices by facilities component. The objectives of their proposed approach are to minimize life cycle costs, maximize performance, and manage risk (*58*). Matichich, presenting at FTA's Second State of Good Repair Roundtable, describes an asset management approach used in the water/wastewater industries (*59*). Improving asset management has been a focus area in these industries, as in transportation. Analyses of investment needs typically focus on existing condition and use failure risk as a measure for prioritizing investments.

Analytical Approaches for Highway Assets

The resources described in Section 2.2.1 summarize the state-of-the-practice and state-of-the-art for analyzing asset rehabilitation and replacement investments in highways and other transit-related industries. Of these resources *NCHRP Report 545* specifically focuses on available analytical tools (*16*) and *NCHRP Report 632* (*17*) updates the review in *NCHRP Report 545*.

Generally speaking, analytical approaches for addressing asset rehabilitation and replacement needs are most sophisticated for highway assets, particularly pavement and bridges.

Commercially available pavement management systems allow for specification of complex decision trees for defining feasible maintenance, repair, and rehabilitation actions; support flexible specification of deterioration models based on condition, time, environmental conditions, and other variables; and incorporate optimization and simulation models that allow an end user to determine what actions should be taken to achieve a given condition target or that maximize use of available resources. FHWA's Highway Economic Requirements System (HERS) and World Road Association (PIARC) HDM-4 model pavements at a less detailed level than the commercially available systems and are less flexible in their designs, but add consideration of needs for capacity expansion and consideration of user costs. For bridges, the AASHTO Pontis Bridge Management System and FHWA National Bridge Investment Analysis System (NBIAS) use optimization models to determine the life cycle cost minimizing policy for maintaining the individual structural elements of a bridge. Other bridge management systems of similar complexity have been developed for use internationally. There are fewer examples of approaches used for analyzing rehabilitation and replacement needs for other highway assets besides pavements and bridges. NCHRP Synthesis 371 describes data, tools, and approaches for managing a cross section of different highway assets including signals, lighting, signs, pavement markings, culverts, and sidewalks (*60*).

A particularly important issue in asset management for highways is that of allocation of resources across asset types. The available management systems are generally designed to address assets of a specific type, which makes it a challenge to combine information for different types of needs and assets. Combining consideration of multiple asset types is an issue both when determining how to allocate assets at a high level between asset/investment categories and when prioritizing projects.

For high-level resource allocation, two basic approaches are predominant: subjective comparison of performance using key measures established by asset/investment category and more formal optimization approaches that systematically evaluate utility across multiple aspects or objectives. A number of DOTs have established performance measures, and examine predicted performance in terms of their key measures to determine how to allocate across asset or investment types. The case of NJDOT described in Appendix D is illustrative. For developing its capital investment strategy, NJDOT, working with New Jersey Transit (NJ Transit) and other planning partners, has established performance measures by asset/investment area, and predicts future performance for these measures for a set of six investment scenarios. These projections are updated annually in New Jersey's Capital Investment Strategy document (*61*).

In several cases, organizations have used the AssetManager NT tool described in *NCHRP Report 545* (*16*) to analyze predicted conditions across asset types. Guerre and Evan describe an effort by the Southeast Michigan Council of Governments (SEMCOG) to perform a high-level resource allocation across pavements, bridges, highway capacity, safety, transit, and non-motorized projects using AssetManager NT (*62*).

A number of the materials reviewed describe multi-objective optimization approaches for allocating resources between asset/investment types, such as between pavements and bridges or between different types of bridge investments. Gharaibeh et al. describe the use of multi-attribute utility methodology for allocating funds across asset classes or programs (*63*). Morcous proposes an approach to using multi-criteria optimization for improving bridge preservation decisions (*64*). *NCHRP Report 590* includes a comprehensive review of multi-objective optimization approaches and describes use of multi-objective optimization for bridge management (*65*). Dehghanisanij et al. describe an ongoing research effort to develop a framework for optimizing cross-asset resource allocation decisions and review the alternative optimization approaches (*66*). An example of a practical application of multi-objective optimization is a model for resource allocation between pavements and bridges developed for New Brunswick DOT, which uses a model originally developed for the forestry industry *(67)*.

Cross-asset resource allocation is also an issue in prioritizing specific projects. The literature provides a number of examples of different scoring and other prioritization approaches, but in most cases these have been used for prioritizing major improvement projects, not asset rehabilitation and replacement projects. For instance, Lambert et al. describe a prioritization approach developed for Virginia DOT to coordinate and prioritize large scale multimodal investment network projects for Virginia's long range transportation plan (*68*). The approach described is typical: performance measures are proposed for six different criteria and projects are scored using different alternative sets of weights for the criteria. Louch et al. review different approaches for project prioritization and propose an approach combining optimization and scoring approaches (*69*). Cross-asset prioritization approaches (e.g., scoring projects) for highway projects tend to consider a narrower range of variables than the asset-specific prioritization approaches incorporated in pavement and bridge management systems. For instance, scoring approaches can highlight what assets are in the worst condition, but are less suited for selecting the set of projects that, if performed, will minimize life cycle costs. Thus, particularly for smaller projects, it is often sufficient to prioritize investments within asset categories using existing management systems or other approaches once a high-level budget allocation has been established.

Summary of Findings

The following bullets are the findings of the review with respect to analytical approaches for asset rehabilitation and replacement:

- The approaches used for analyzing transit asset rehabilitation and replacement needs are predominantly age-based models that involve expected service life and age of an asset. Even in condition-based models, such as in TERM, conditions are estimated and predicted to change based strictly on asset age. They predict the costs of rehabilitation and replacement required to achieve an age-based set of standards and can predict measures such as average age and condition. However, these approaches do not provide any direct predictions of other measures of system performance and are of limited value in prioritizing investments when available funds are insufficient for addressing all identified needs.
- Two of the approaches used by transit agencies in practice provide predictive capabilities beyond those in age-based models. The MBTA SGR Database can help prioritize investments when available funds cannot address all identified needs, and thus can support analysis of the impacts of different investment levels. LU's performance reporting approach translates asset conditions and maintenance levels into impacts on passenger journey time and delay (lost customer hours). This approach facilitates further analysis of the impacts of rehabilitation and replacement decisions and provides a metric for prioritizing investments between asset types.
- Several other transit asset analytical approaches identified in the review could be adapted to help analyze the impacts and implications of asset investments and/or prioritize asset investments at a high level. In particular, the review yielded several efforts to better relate asset age and conditions to maintenance and life cycle costs.
- Across industries, the review found that analytical approaches are used more frequently for supporting high-level analysis of asset investments, in contrast to project prioritization decisions. Project-level decisions must be made considering a number of factors and constraints that are less amenable to systematic analysis than high-level budget allocation. Nonetheless, a variety of optimization and scoring approaches have been developed for supporting project prioritization for transit and other assets.
- Analytical approaches used for highway assets may provide insights in the development of new and/or more sophisticated approaches for analysis of transit investments. In particular, the modeling approaches used for pavement and highway assets are well-developed and documented, and incorporate consideration of a wide variety of factors. For example, during high-level budget allocation, performance in terms of key performance measures is predicted for a range of investment scenarios. To address the difficulty in comparing investments for different asset types (e.g., vehicles and track), this approach frequently employed for analyzing highway assets can be adapted.

SECTION 3

Characterizing Investment Impacts and Implications

3.1 Overview

> *Transportation systems are the backbone of America: They keep our nation strong and moving. But we have not been taking good care of this resource. Lacking a coherent vision for our transportation future and chronically short of resources, we defer new investments, fail to plan, and allow existing systems to fall into disrepair.*
>
> —*Gerald Baliles and Jeffrey Shane* (70)

The importance of investing in preserving the nation's transportation system is a theme that many U.S. transportation professionals and leaders have emphasized in recent years. The existing system is aging and there is a need to continually rehabilitate and replace transportation assets that comprise the nation's transportation system to maximize its performance. This concern extends to all elements of the system, but is particularly pronounced in the case of transit. Many transit agencies face a situation in which a large portion of their vehicles and fixed assets are either nearing the end of their useful life or have already exceeded it. FTA's *National State of Good Repair Assessment (1)* details the scope of the issue in terms of the necessary investment required to achieve a state of good repair, which entails replacing assets deemed to have reached the end of their useful life.

A major limitation of approaches to characterizing rehabilitation and replacement needs for transit assets has been a lack of quantification of the impacts and implications of underinvestment. Existing models and approaches described in Section 2, such as FTA's TERM, help describe *how much* investment is needed, but are not well-suited for communicating *why* funds are needed for rehabilitation and replacement, or *what* the consequences are—positive and negative—of investing at a given level. Without this information, it is exceedingly difficult to effectively prioritize among competing rehabilitation and replacement needs when funds are limited.

This section describes the impacts and implications of investing in rehabilitation and replacement of existing transit assets. Section 3.2 provides several documented examples of these impacts. Section 3.3 presents an approach for categorizing the more quantifiable impacts and implications. Section 3.4 discusses other impacts and implications that are more indirect and/or difficult to quantify.

3.2 Examples of Impacts and Implications

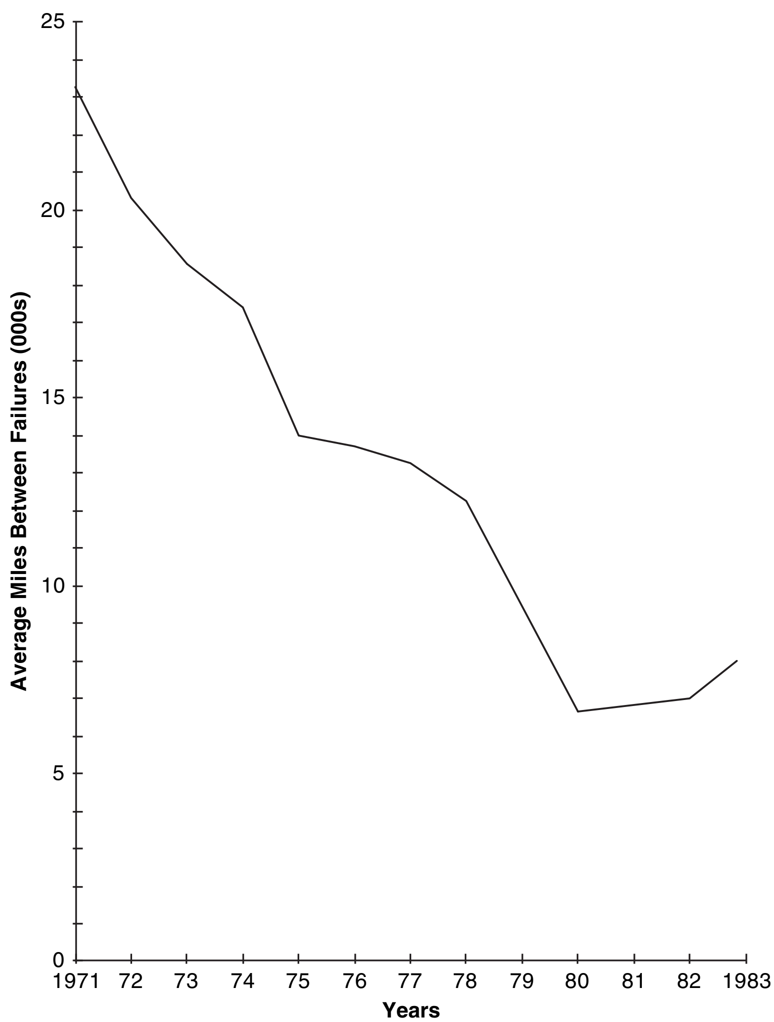
The impacts of asset rehabilitation and replacement investments are most conspicuous in their absence. Generally, the intended result of rehabilitating or replacing an existing asset is to ensure that the service the asset provides continues. This quality is certainly desirable, but its benefits are difficult to measure and easily taken for granted. In contrast, the disbenefits of degrading an existing service by not rehabilitating or replacing an asset are more obvious and more easily quantified. We can observe how people are delayed, inconvenienced, or otherwise impacted by the decline in the reliability—or outright removal—of an asset, and compare the results to prior conditions. Alternatively, once a badly needed service is restored through asset rehabilitation or replacement, we can observe the impacts of the restoration of service. In either case, it is the fact that a needed rehabilitation or replacement was deferred that provides the information needed to assess the impacts.

New York City Transit Authority

In this vein, perhaps the most illustrative and well-documented example of the impacts and implications of investment in existing transit assets is that of New York City. In the 1970s, New York City's transit system (along with much else in the city) entered a period of steep decline. The city's finances were badly strained throughout the first half of the decade and a budget crisis from 1974 to 1975 nearly resulted in the city declaring bankruptcy. New York's budget woes translated into chronic deferral of needed maintenance, rehabilitation and replacement of New York City Transit (NYCT) assets. In a remarkable set of case studies prepared for FTA, Kuiper describes the decline of the system during the period and details its impacts on NYCT rail cars (the R-36 fleet, in particular) and track (*71*).

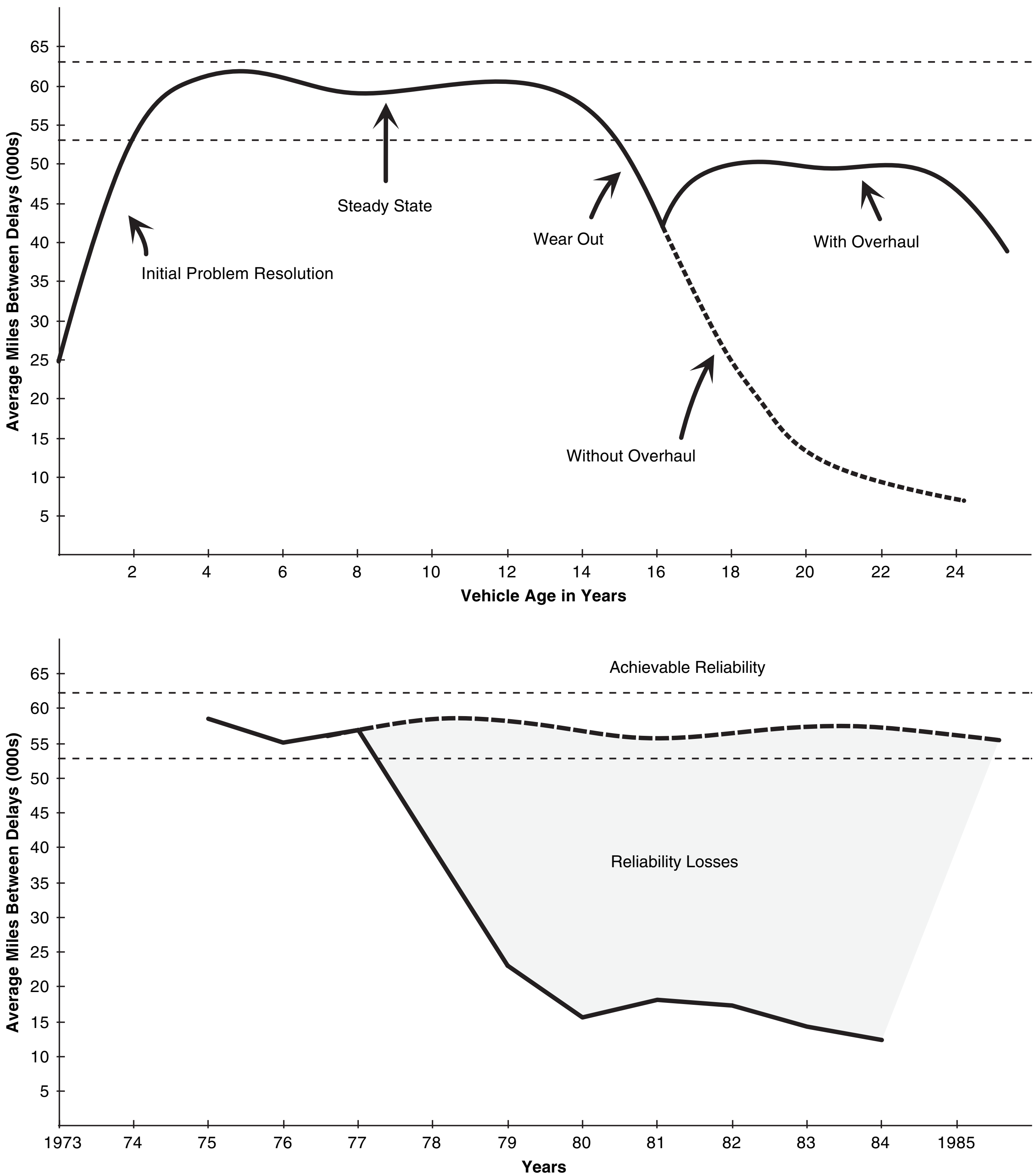
The reliability of NYCT's rail fleet declined throughout the 1970s. Figure 3-1, reproduced from Kuiper's report, shows that the MDBF for the fleet dropped from approximately 23,000 miles in 1971 to 7,000 miles in 1980 and recovered to approximately 9,000 miles in 1983. In the case of the R-36 fleet, the reliability of this fleet was significantly higher than the system average at the beginning of the 1970s (as the fleet was procured in 1964), but its reliability declined. The MDBF dropped from approximately 58,000 miles in 1977 to 16,000 in 1980. Kuiper attributes the decline to staff turnover, an increase in the inspection interval, and deferral of needed maintenance, repair and rehabilitation actions. Figure 3-2 shows the impact of underinvestment on the reliability of the R-36 fleet. The top graph shows a theoretical reliability curve of the life of a rail fleet, and the bottom graph shows the actual performance of the R-36 fleet over time.

Kuiper also details the effects of deferral of rail replacement at NYCT, comparing actual to expected rail replacements for the period from 1971 to 1983. Given the life and weight of rail at that time, Kuiper estimates that NYCT would have, in a steady-state condition, replaced approximately 11,400 tons per year (65 miles). In actuality, the amount of rail replaced declined from 13,000 tons in 1971 (and more than 14,000 in 1972 and 1973) to 7,256 tons in 1983. The report calculates the cumulative deferral of rail replacement totaled 18,494 tons during this period. As a result of this deferral, by the end of the analysis period, 54% of NYCT's track was classified as requiring either replacement of major components (Class C) or complete reconstruction (Class D) within seven years.



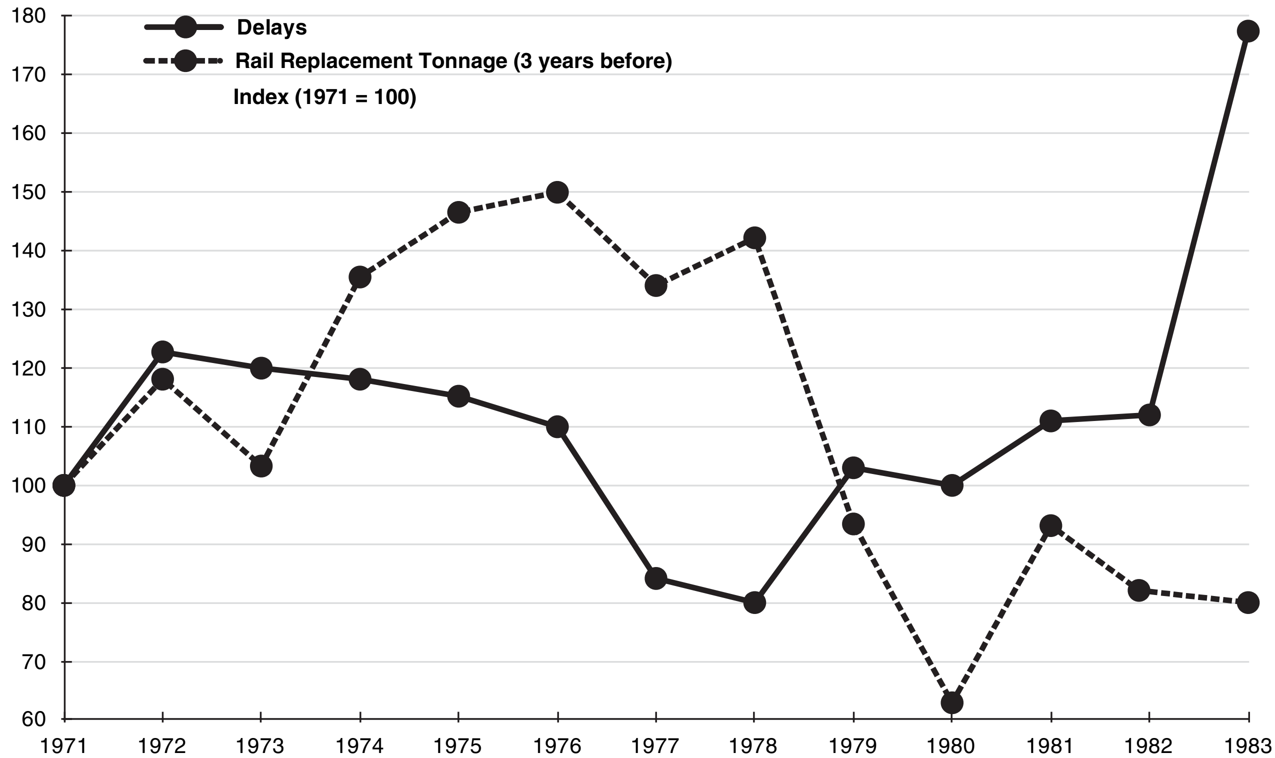
Source: Kuiper (*71*)

Figure 3-1. NYCT rail fleet reliability from 1971 to 1983.



Source: Kuiper (*71*)

Figure 3-2. Theoretical and actual reliability for the NYCT R-36 fleet.



Source: Kuiper (*71*)

Figure 3-3. Comparison of NYCT rail replacement and delays from 1971 to 1983.

The immediate impact of deferral of needed rail replacement was an increase in delays. Figure 3-3 from Kuiper's report shows the quantity of rail replaced versus delays, with the two indexed to a value of 100 in 1971, and with replacements offset three years to reflect the time required for deferral of rail replacement to impact day-to-day performance. The figure shows that relative to 1971, delays had increased by approximately 80% by 1983 as a result of the deferrals in rail replacement.

In the 1980s, NYCT began to recover from its period of decline, and the results of that recovery are indeed striking. Boylan (*72*) summarizes the impacts of NYCT's turnaround. In the period from the early 1980s through the end of 2008, the Metropolitan Transportation Authority (MTA) invested/reinvested an estimated $74 billion in its state-of-good-repair needs in NYCT and other MTA properties. For NYCT, this translated into rehabilitation or replacement of approximately 6,000 rail cars, 700 miles of track, and 200 stations, as well as other investments. Between 1982 and 2007, MTA achieved many positive impacts from rehabilitation and replacement investments:

- Increase in subway reliability of 155%;
- Reduction in subway delays of 59%;
- Increase in average MDBF from under 7,000 miles to more than 156,000 miles (Statistics in NYCT's monthly operating reports provide additional insight into this statistic. For older fleets, MDBF is typically 60,000 to 100,000 miles, while for newer fleets this value is sometimes more than 200,000 miles.); and
- Ridership growth of 58% from 1982 to 2007 for all MTA properties, in contrast to a 17% reduction in the 1970s.

Chicago Transit Authority

Experiences from other transit agencies provide several other examples of the negative impacts of deferral of investment in existing assets, as well as of the positive impacts of addressing deferred investments. Chicago Transit Authority (CTA) has faced a number of challenges in maintaining its system, and has documented some of the impacts and implications of investments in existing assets. One of the primary impacts of deferred rehabilitation and replacement work on CTA's system concerns the extent of slow zones. Perhaps because much of CTA's system is or has been under slow orders, the existence of slow zones is often noted in descriptions of the state of the repair of the system (*73, 74*). Also, as noted in Section 2, CTA publishes statistics on the extent of slow zones in its performance reports, and this information (including maps showing extent of slow zones) is published on CTA's Web site.

A notable example of this issue is the case of the Douglas Branch of the Blue Line (now the Pink Line). This branch was originally built beginning in 1896. By the late 1990s, the physical conditions of the branch had deteriorated to the point that much of the system was under slow orders, trip times (from the 54th Street/Cermak Station to Chicago's Loop) had increased from 25 to 45 minutes, and ridership had dropped 50% (*74*). In 2001, CTA began an extensive rehabilitation of the Douglas Branch. This work was completed in 2005. The rehabilitation and replacement work, coupled with a subsequent minor rerouting of the branch near the Loop, reduced trip times significantly and helped increase ridership.

When deteriorated conditions are left unaddressed, poor asset conditions may lead to accidents or loss of service. Unfortunately, CTA offers examples of these negative impacts. In 2006, CTA experienced a derailment on its Blue Line, which resulted in 152 injuries. The National Transportation Safety Board (NTSB) determined that corroded rail fasteners caused the accident although the problem was compounded by CTA's inspection, training and management practices (*73*). Prior to the rehabilitation, service to stations beyond 54th Street/Cermak on the Douglas Branch was discontinued due to a combination of low ridership and poor asset conditions.

Toronto Transit Commission

Toronto Transit Commission (TTC) offers another example of the negative impacts of deferring asset investments. In 1995, TTC suffered an accident in its subway system at Russell Hill when one train rear-ended another, killing three people and injuring 36. Though the accident was attributed to a combination of human error and an antiquated signal system, it galvanized TTC to focus on achieving a state-of-good-repair under its new General Manager David Gunn (*8*). TTC committed to a "life-cycle approach to maintenance." Asset conditions were improved as a result of this focus, but this required deferral of a number of expansion initiatives.

U.S. Bus Transit Systems

The first examples concern impacts and implications of investments in rail systems. However, for bus systems, the issues related to investments in existing assets are no less pressing. General information on the impacts and implications of bus replacement timing is available in *Useful Life of Transit Buses and Vans* (*55*). This report describes the results of a survey of U.S. bus operators on the possibility of extending FTA service life requirements for buses. Agencies reported the following potential impacts:

- Higher failure rate;
- Lower reliability;
- Increased customer complaints;
- Increase in maintenance costs of 10% to 50%; and
- Less flexibility to retire "problem" vehicles.

3.3 Impact Categorization

Maintaining a state of good repair can be viewed as a problem of maximizing economic efficiency—with a range of economic and non-economic consequences resulting from decreased efficiency. Figure 3-4 shows the basic relationship between the timing of major interventions for a capital asset (e.g., rehabilitation or replacement) and the cost of purchasing and maintaining the asset over its life. As shown in the figure, the optimal point to perform an intervention exists where the life cycle cost is lowest. This point depends upon the asset type, type of intervention, and a range of other variables, and thus can be difficult to predict precisely. Recommendations on when to rehabilitate or replace an asset are typically intended to achieve this optimum, cost-minimizing point. More frequent interventions (e.g., replacing buses at eight years rather than 12) may result in a higher level of service, but this service comes at a cost. Fewer interventions—deferring needed rehabilitation or replacement actions—result in a lower level of service (e.g., due to more frequent in-service failures) and higher costs. Savings from the deferral are exceeded by cost increases due to higher maintenance needs associated with older equipment.

Economic efficiency may be at the root of state-of-good-repair concerns, but as the examples in the previous section illustrate, there are a number of practical implications to this somewhat abstract concept. Figure 3-5 illustrates the relationship between rehabilitation and replacement actions and the impacts of those actions in terms of asset conditions, and a range of other issues.

The figure shows that transit agency standards, along with available funding, help determine rehabilitation and replacement actions. Rehabilitation or replacement of an asset changes its state of repair. The state of repair of an asset can be characterized using a variety of measures. Depending on the asset, one may approximate its condition using a condition rating, the age of the asset, its mileage, or other variables. In any case, changing asset characteristics can impact three areas directly related to the performance of the asset: the availability of the asset (capacity to perform service); reliability (the likelihood it will remain in service at any given time); and the overall quality of the service the asset provides. For instance, if an asset is replaced, one would expect the new asset to have higher availability, be more reliable, and provide better service than the asset it replaced. Likewise, if needed action is deferred, one would expect the availability, reliability, and service quality associated with the asset to drop.

The asset-specific impacts illustrated in the figure are readily measurable and closely tied to asset conditions and

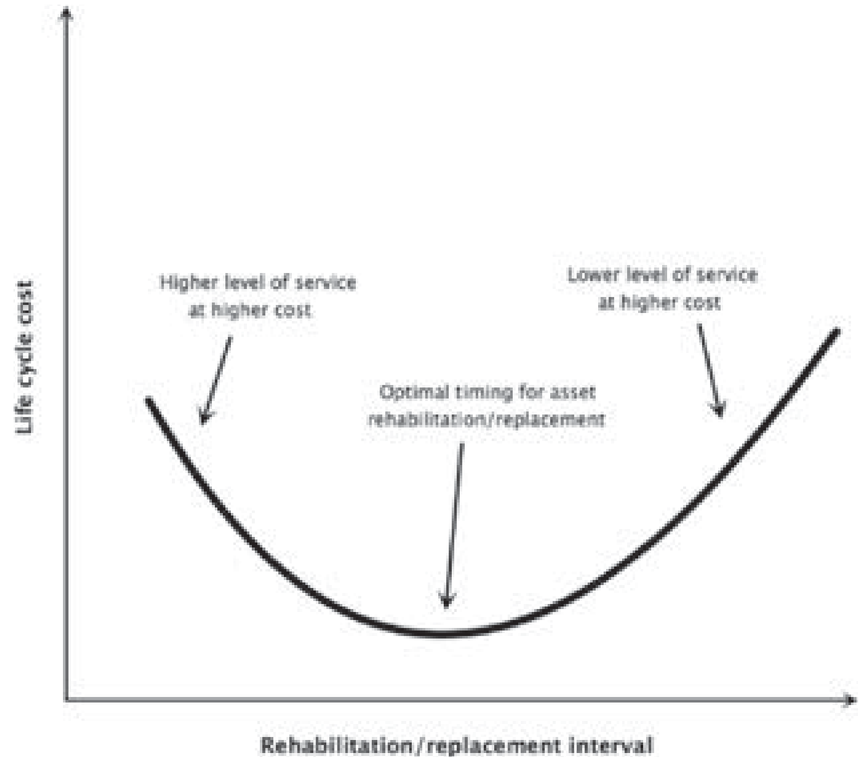


Figure 3-4. Relationship between life cycle cost and intervention interval.

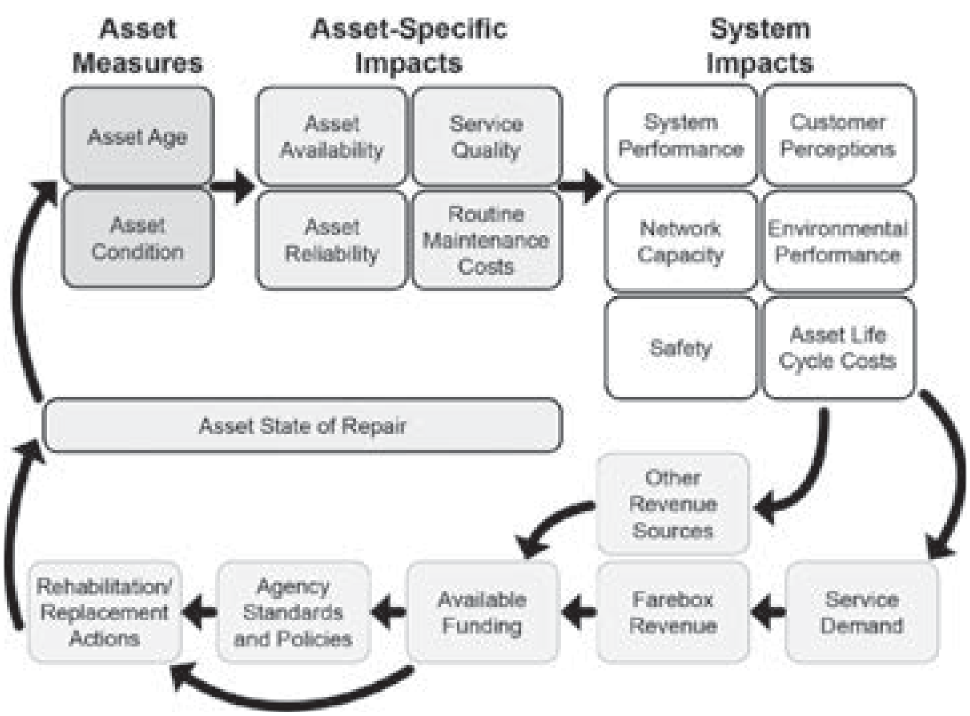


Figure 3-5. Impacts and implications of rehabilitation and replacement actions.

are only part of the story. Asset availability, reliability, and service quality ultimately impact:

- Overall performance of the system (on-time performance);
- Network capacity (by determining the upper limit of vehicle availability and/or speed of the network);
- Safety;
- Customer perceptions;
- Environmental performance (e.g., noise and emissions); and
- Life cycle costs.

These bullets are known as "system" impacts as they are either more difficult to measure or result from a number of other factors besides asset conditions. Generally speaking, performance measures have already been defined and are monitored for these categories, but they may not be related to state-of-good-repair concerns. For instance, the review described in Section 2 identified several cases where transit agencies report delays (a measure of reliability), but only one where the transit agency relates delay incidents back to overall system performance (LU, which relates asset conditions to journey time and lost customer hours). But even if the relationship between rehabilitation and replacement actions and the system impacts is less direct, the system impacts identified in the figure are important because they include the areas of greatest importance to the transit passenger. As an example, a transit passenger may not be immediately impacted by an increase in MDBF or spare ratios from deferral of needed bus replacements, but if increases in those measures translate into delay or an increase in accidents, then the deferral may begin to be a passenger concern.

The system impacts shown in the figure can ultimately impact demand (ridership) and available funding. If the service on a system is extremely poor, then the system will lose riders as CTA's Douglas Branch and New York City's transit system did. The worst case is what Boylan describes as the "death spiral" experienced in New York, in which the city's funding crisis contributed to condition declines that lead to drops in ridership and more emergency repairs, which further exacerbated the fiscal situation (*72*). But impacts to demand and available funds are even more difficult to measure than the other impacts illustrated in the figure because they are affected by an even greater set of external factors and are of less immediate concern to an individual user. Thus, they are handled as separate issues for the purpose of this discussion.

Table 3-1 supplements the list of impacts with representative performance measures, with additional notes regarding what measures can be measured and predicted in relationship to asset conditions. As noted in the table, measures of asset availability and reliability are readily measurable and can be related to asset conditions. Most of the system impacts, even if measurable, are more difficult to relate to asset conditions.

3.4 Other Impacts

Figure 3-5 and Table 3-1 detail many of the impacts and implications of transit asset investments, focusing on those that are most readily measurable. The case studies described in Appendix A and the examples in Section 3.2 describe a number of other impacts and implications not shown in the figure and table. Table 3-2 lists other impacts and implications of asset investments.

Table 3-1. Impacts and corresponding performance measures.

Category	Related Measure Type	Example Measures	Notes
Asset Measures	Age	Average Age of Assets as a Percent of Their Useful Life, Accumulated Mileage	Readily measurable and easy to predict, often used as a proxy for asset condition
	Condition	Condition Rating, Percent of Assets in Good/Fair/Poor Conditions	Readily measurable and predicted, but is more difficult to measure and predict than age
Asset Availability	Quantity Available for Intended Use	Percent of Slow Zone Mileage, Minutes of Impact of Speed Restrictions	Readily measurable, impacts noted in NYCT, CTA example and bus agency interviews
	Spare Ratio	Ratio of Spare Vehicle Quantity to Fleet Size	
Asset Reliability	Failure Rate	Mean Time/Distance Between Failures	
	Delay	Lost Customer Hours	

(continued on next page)

Table 3-1. (Continued).

Category	Related Measure Type	Example Measures	Notes
Service Quality	Passenger Comfort and Convenience	Ambience Score	Less readily measurable and difficult to predict
System Performance	On-Time Performance	Percent of Trips Late	Measurable, but difficult to predict as a function of asset conditions
Network Capacity	Total Capacity	Peak Hour Passenger Capacity	
Safety	Accident Rate	Accidents per million train/bus miles	
Customer Perceptions	Customer Satisfaction	Customer Satisfaction Rating, Number of Customer Complaints/Passenger	
Environmental Performance	Noise	L_{max}, L_{eq}	Readily measurable, can be predicted, particularly for buses
	Emissions	Tons of pollutants emitted (e.g., CO_2)	
Asset Life Cycle Costs	Maintenance Cost	Maintenance Cost per Revenue Mile/Hour	

Table 3-2. Other potential impacts and implications.

Impact/ Implication	If Needed Rehabilitation/ Replacement Investments Are Made	If Needed Investments Are Deferred
System Enhancements	It may be possible to make minor near-term system enhancements as part of the rehabilitation/replacement investment, though larger improvements may need be deferred.	It may be possible to make system enhancements in the short term, but this may only exacerbate the challenge of preserving the system over the long term.
Maintenance Productivity	Productivity should improve as the reduced maintenance demands of new assets allow for more proactive planning and preventive maintenance.	Productivity is hampered by necessity of making emergency repairs, increasing overtime and resulting in maintenance staff operating in a less productive, reactive mode.
Service Flexibility	Availability of newer assets in better condition may increase flexibility of the system to adapt to new demands.	Transit agency flexibility to adapt to new demands is constrained.
Transit Agency Accountability	Accountability is strengthened. Stakeholders and the public may be supportive of increased investment if asset rehabilitation and replacement investments are perceived favorably.	Stakeholders and the public may lose faith in transit agency management and decision making.

SECTION 4

Framework for Prioritizing Transit Asset Rehabilitation and Replacement

4.1 Introduction

This section describes a framework for transit agencies to use for prioritization of capital asset rehabilitation and replacement decisions. The framework builds upon fundamental concepts involved in prioritizing asset rehabilitation and replacement decisions and provides a basic set of steps for transit agencies to follow. By applying this framework, a decision maker can answer questions about asset rehabilitation and replacement investment decisions illustrated in Figure 4-1, including:

- What funds are required to perform recommended asset rehabilitation and replacement work?
- How will asset rehabilitation and replacement impact transit performance?
- What are the relative impacts and implications of different funding levels?
- How should available funds be prioritized?

Section 4.2 describes basic concepts of performance and asset management that support the framework, with references to other sections of this document and other resources that detail these concepts further. Section 4.3 presents a step-by-step process for making asset rehabilitation and replacement decisions with case study examples that illustrate how agencies such as the MBTA, MTC, and King County Metro have made decisions about transit asset rehabilitation and replacement. Section 4.4 provides a summary of the framework.

4.2 Fundamental Concepts

In order to apply the framework, information from three key areas is required: rehabilitation and replacement actions, performance measures, and investment. Information on rehabilitation and replacement actions provides decision makers with options to determine which assets to replace or rehabilitate. Ideally, these decisions are based on an "optimal policy" that specifies the actions and action timing to minimize costs and maximize performance over time. The decisions are based upon consideration of the baseline set of actions required to comply with legal requirements to achieve the minimum threshold for safety, performance, and other considerations.

Performance measures are used to characterize how well assets are functioning and to communicate impacts of investments to support decision making. Determining how a set of investments would impact performance provides a basic way to clarify trade-offs and make decisions about what assets to rehabilitate or replace given limited funds and competing objectives. Information is also needed on investment levels. This includes specification of what funds are available for asset rehabilitation and replacement and constraints on the use of the funds, such as on timing or type of actions or assets that can be funded. Figure 4-1 represents these elements and relationships in a conceptual model of the decision-making framework.

Determining When to Rehabilitate or Replace an Asset

In deciding when to rehabilitate or replace an asset one typically assumes that an asset has a finite, though perhaps indeterminate, life and that one can calculate the life cycle cost of the asset. Below is a summary of the assumptions concerning life cycle cost, asset life, and the development of an optimal policy that form the basis for determining when to rehabilitate or replace an asset.

Life cycle cost provides a measure of the cost of an asset over the course of its life. Life cycle costs are often presented on an average annual basis to facilitate comparison between assets with different lives. The calculation of life cycle costs always includes costs borne by the owner and operator of the asset (transit agency costs, in the context of transit assets), and may include costs associated with use of the asset (user costs).

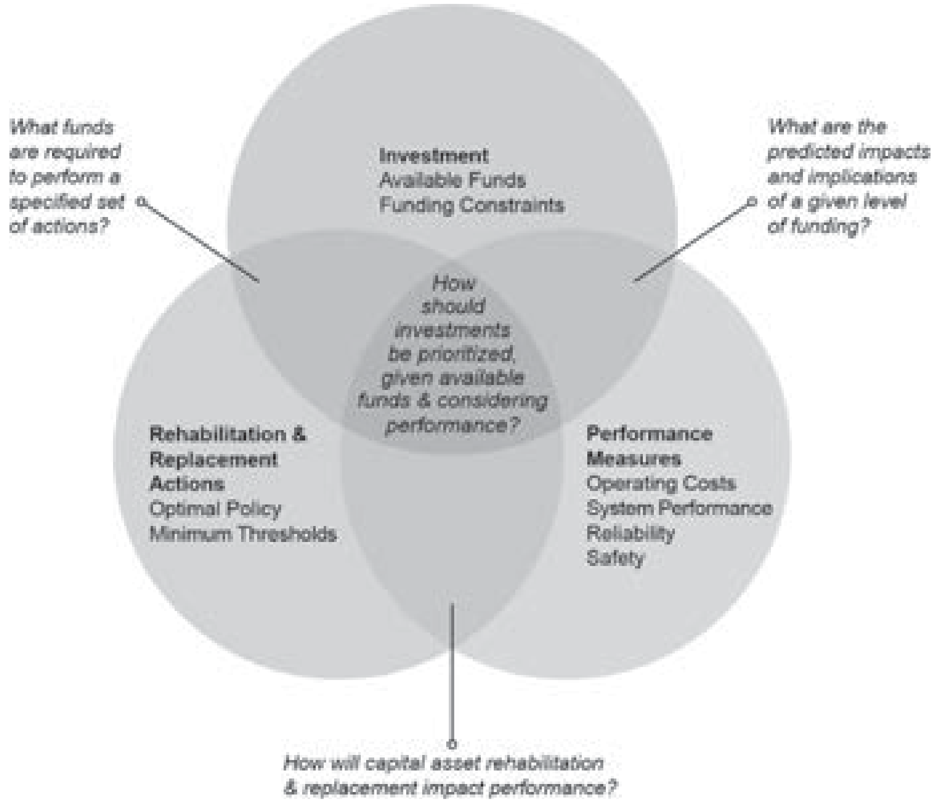


Figure 4-1. Elements of the decision-making framework.

The determination of exactly what costs are included in an analysis depends in large part upon what options the decision maker is weighing. For example, if one is considering two alternative designs with the same user costs then user costs would typically be omitted from the calculation. As described by Martland (*75*), transit agency costs included in the calculation of life cycle cost may include:

- Asset purchase (incorporating materials/component purchase, production and transport);
- Construction;
- Inspection;
- Maintenance;
- Rehabilitation;
- Replacement/salvage; and
- Asset failure.

If desired, high-level soft costs (e.g., general administration, financing) can be estimated as a percent of overall hard costs by asset type in order to provide a more complete assessment of the full cost of asset replacement.

Figure 4-2 illustrates the calculation of life cycle cost for a typical asset. The bars indicate costs incurred each year. The cost shown the first year represents the purchase/construction cost. A gradually increasing maintenance cost is incurred each year, with a mid-life rehabilitation of the asset and replacement of the asset at the end of its life. Note that if the asset were salvaged at the end of its life and not replaced, there would be a negative cost at the end of the asset life associated with salvage of the asset. Also shown in the graph is the sum of costs over time considering discounting, approximating the time value of money. This represents the life cycle cost of the asset.

Asset life. The *service life* of an asset is the amount of time it is expected to perform at a specified level of service, and the *remaining service life* (RSL) is the difference between this time and the age of the asset. The appropriate units to use for characterizing the life of an asset vary based on how the asset deteriorates. For many assets, asset life can best be characterized in units of time, but in other cases measures of use (e.g., vehicle miles) may be a better predictor of asset life. RSL is a useful measure, but does not necessarily indicate the time until an asset must be replaced. Often once an asset has reached the end of its service life, its life can be extended through rehabilitation or overhaul.

In Figure 4-2, the replacement of the asset marks the end of the asset's life. This replacement could be motivated by any number of events. It could represent the point at which the asset can no longer function as it was originally intended, when it is deemed to be obsolete, or simply when

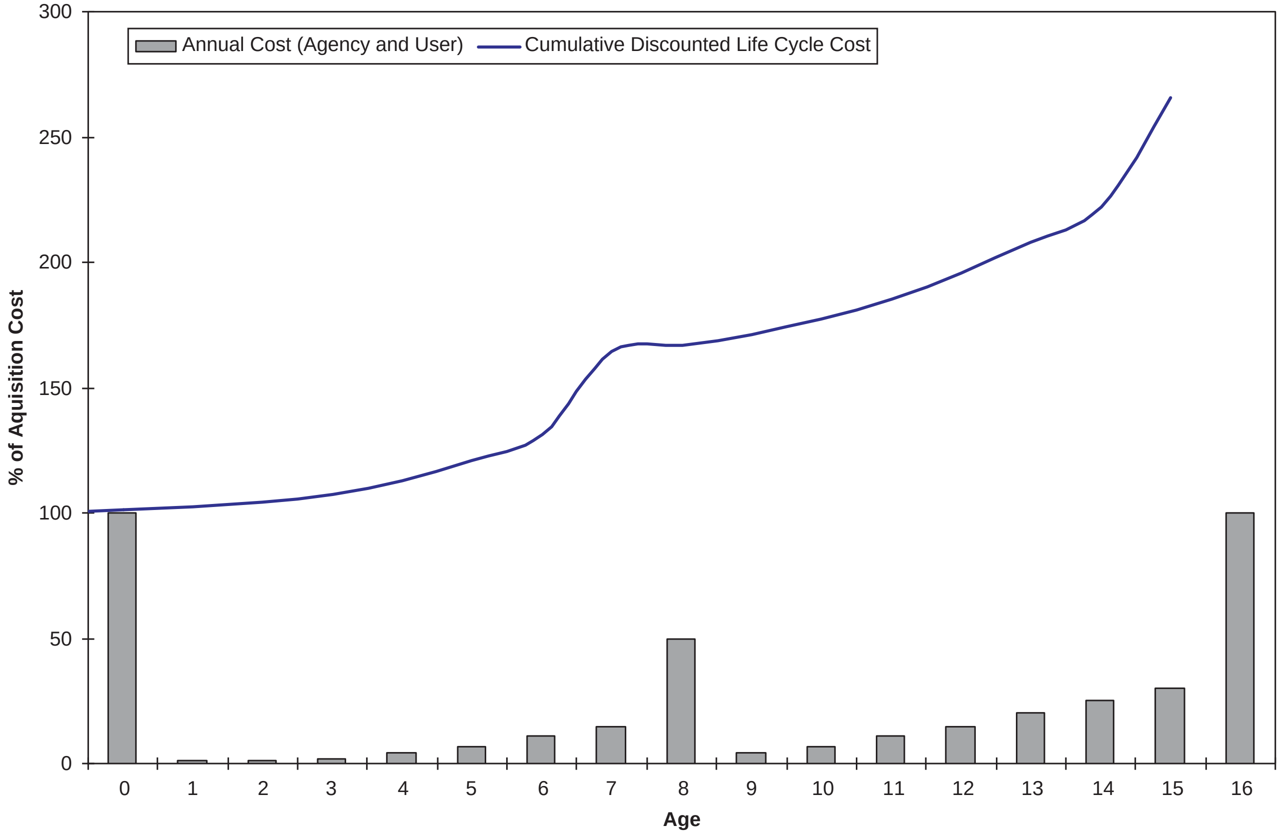


Figure 4-2. Typical asset life cycle.

the cost to maintain the asset is greater than the cost of replacing it. The asset could also reach its end-of-life by failing prematurely.

Knowing how long the asset is expected to last, and the likelihood that it will fail before it reaches its expected life, is important for any rehabilitation or replacement. The assumption that an asset has a finite life may seem intuitively obvious. However, this assumption often fails to hold true for complex assets and assets with long lives. For example, a section of rail has a finite life, but a rail system viewed as a whole would generally be seen as a "going concern" that does not have a finite life. Likewise, individual elements or components of a bridge (e.g., girders or beams) may have finite lives, but most bridge management systems model bridges as long-lived assets that can be maintained indefinitely if needed maintenance, repair, and rehabilitation actions are performed. A facility is another example of a complex asset often treated as a going concern for which it is important to consider component-level data. For complex assets, then, it is important that the asset be represented at the element or component level, both to accurately characterize asset life and to more realistically reflect what rehabilitation or replacement actions are needed at any given time. It is worth noting, however, that the added accuracy and realism obtained by characterizing complex assets at the element or component level can entail substantial added effort expended on data acquisition and maintenance.

Developing an optimal policy. An optimal policy for an asset represents the set of actions to perform on the asset over time to minimize life cycle costs. Given information on the life cycle costs of an asset, and information on asset life, one can determine an optimal policy for that asset. The actions that the policy includes, and the triggers for those actions, depend upon a number of asset-specific calculations. Figure 3-4 in Section 3 shows an example of such a calculation. Section 5 summarizes different approaches to determining the optimal rehabilitation and replacement policy for an asset.

Measuring Asset Performance

Ultimately, decisions concerning rehabilitation and replacement of transit assets are motivated by the goal of maintaining or improving performance. Transit assets—vehicles, guideway, facilities, or other physical elements of a transit system—exist to provide a service. Performance measures help quantify the service these assets provide. In concept one should ask a series of questions about an asset's performance when determining what actions to take on the asset and the appropriate timing for those actions.

In considering whether and when to replace an asset, it is useful to address three questions: how the asset helps the transit agency achieve its performance goals, how performance varies as the asset ages and/or deteriorates, and what the impact on performance would be if the asset failed or was removed from service. Section 3 describes the impacts and implications of asset rehabilitation and replacement decisions, and Table 3-1 in that section relates these to specific performance measures. In general, it is the system-wide measures of performance that are of greatest importance from the perspective of the transit customer. However, it is at best difficult and at worst infeasible to relate the performance of a specific asset to the performance of the overall system.

Selecting performance measures for resource allocation is a balancing act. No one performance measure has all of the desired attributes, and many common and useful measures have one or more decidedly *undesirable* attributes. Precisely because the challenge of selecting measures for resource allocation is one of striking a balance, the rules of thumb that commonly appear in the performance management literature tend to be useful primarily for clarifying the issues rather than suggesting solutions. Two of these common rules of thumb are presented here: *leading versus lagging indicators* and *outcomes versus outputs.*

Leading versus lagging indicators. One rule of thumb is that *leading* indicators are generally preferred to *lagging* indicators; a leading indicator provides information on where a system is headed, while a lagging indicator reflects where it has been. Leading indicators of a transit system's state of repair include the amount invested in the system and the percentage of assets in excellent condition. If these indicators decline one can expect a future, though not immediate, reduction in the state of repair. A measure such as mean time or distance to failure is a lagging indicator in that the value of the measure at a given point is the product of many maintenance and operating decisions made over time, and decisions made today will not result in immediate changes to this measure. On the other hand, lagging indicators often tend to be those for which the best trend data are available, and that best support a long-term view of performance. For example, in (*71*) data on mean distance to failure provides useful information on performance trends for the New York City Transit system in the 1970s that can be compared to today's data to provide a perspective on how system performance has changed over time.

Outcomes versus outputs. Another rule is that measures of *outcomes* are generally preferred to measures of *outputs.* This is certainly true, but outcome measures (e.g., passenger boardings or on-time performance) are often more difficult to measure and less amenable to predictions of future conditions and use for decision support than the more mundane output measures (e.g., miles of track or numbers of vehicles replaced).

A basic strategy for selecting performance measures to evaluate asset rehabilitation and replacement decisions considering the factors discussed above is:

- Recognize that measures used to support resource allocation decisions may be different from those used for other purposes, such as tracking employee performance, supporting long-term planning, or using public reporting. However, where possible these measures should be aligned.
- Identify at least one key measure for each asset type, using common measures across types where possible to avoid "apples versus oranges" comparisons.
- Where it is not possible to identify measures that address all of the considerations discussed above, develop predictive or statistical models for relating one measure to another. For instance, the vehicle model described in the next section relates the accumulated mileage of a vehicle to mean distance to failure and passenger delay.
- Select as few measures as reasonably possible to support resource allocation decisions, avoiding the inflationary tendency of adding more measures to address every aspect of transit agency performance.
- In the event that it is not possible to reconcile all of the competing considerations in selecting appropriate performance measures, the deciding factor in selecting measures for supporting resource allocation is feasibility—a measure is useful only to the extent that it is cost-effective to quantify it.

Prioritizing Investments Based on Multiple Objectives

The problem of determining what investments to select given a set of objectives is a well-defined problem in operations research. Essentially, the problem reduces to an exercise in selecting projects to perform given a set of constraints (most notably a budget constraint) to maximize one's return. Variants of this basic problem which are well-described in the literature include the "diet problem," the "knapsack problem," the "capital budgeting problem," and others.

Utility functions. An important step in framing the problem that transit agencies solve when they prioritize projects in mathematical terms is to introduce the concept of a utility function. A utility function quantifies the overall level of satisfaction one realizes from some decision. If one's objective is to maximize profit or minimize cost, then utility is the same as expected profit. In reality however, most rational decision makers have some degree of risk aversion, and thus will sacrifice some amount of expected profit (or reduced cost) to increase the certainty of a favorable outcome. A decision maker's utility function balances economic return with risk and may incorporate a number of other objectives.

Objectives considered by transit agencies when selecting rehabilitation and replacement projects may include:

- Reducing transit agency costs;
- Reducing asset breakdowns/failures;
- Improving safety;
- Increasing mobility;
- Reducing travel time;
- Improving the quality of service;
- Reducing emissions;
- Addressing environmental justice and equity concerns;
- Improving the environment;
- Increasing economic development potential; and
- Increasing the mode share of transit.

Although the term utility function is used here, other terms that are conceptually equivalent are a project scoring formula, a set of weights on evaluation factors, and other such approaches. Further, though the discussion assumes the existence of a single utility function, in practice projects compete with each other within funding categories and separate utility functions may be used for each category. For example, if a transit agency establishes an overall budget for expansion projects and rehabilitation and replacement projects using scenario analysis, then in theory it is not necessary to describe a single utility function that addresses the benefits of capacity expansion and asset renewal. But often projects do compete for funding across categories and a single project may address multiple needs, which requires a single utility function that can be used to address all of the competing needs. In addition, agencies may use this utility function as a basis for making more fundamental decisions about how to set up those larger funding categories. Section 4.3 describes an example function in which utility is considered to be equal to economic benefit, but it is worth noting that no single correct approach exists for all transit agencies.

Competing priorities. Given the existence of a utility function, the process of optimizing the set of projects would at first appear to be a simple exercise in optimization to select the set of projects that maximizes utility. This sort of problem would appear to be an excellent candidate for use of a systematic solution approach. Alas, the problem is not so simple at all. Complications abound and include:

- Establishing a utility function is nontrivial. Trying to weigh different objectives poses a challenge for most, and the weights different people place on different factors are highly subjective.
- Many constraints in addition to an overall funding constraint add complexity. In reality many funding constraints exist since there are different funds. There are both bundling and capacity constraints that limit the types and amounts of work that can be undertaken at one time. In addition, there are minimum thresholds for certain types of work, modes, and/or geographic areas.
- It is important to consider multiple periods in determining the optimal solution, particularly for long-lived assets. If examining a single period, one might be inclined to defer certain actions (e.g., replacing signals) that one would certainly not defer forever. Considering multiple decision periods, and the impact of decisions made in one period on long-term conditions, often changes the solution considered optimal in the near term.
- Most solution approaches assume that data, particularly costs and outcomes, are defined and certain. In practice, many important variables are undefined, and those that are defined are uncertain. One might quantify costs and impacts of a small set of likely projects, but this does not address the full set of potential projects a transit agency might consider and/or the relative impacts of accelerating or deferring different projects. Also, the "downstream" impacts of a project on quality of service are difficult to predict.
- The basic problem to be solved is an integer programming problem which, like all integer programming problems, has a solution time that grows exponentially with the problem size. Thus, obtaining an exact solution to a reasonably sized problem with a realistic set of constraints may take hours or days to solve, even setting aside most of the other issues listed above.

In short, prioritizing projects is not at all straightforward, despite the fact that it is well understood and appears deceptively simple to the casual observer. Given the many complicating factors, transit agencies that use systematic approaches tend to make simplifications and approximations to keep the process manageable. One strategy is to use a scoring formula/utility function that weights a small set of key factors, and apply the formula to calculate scores for a set of projects to program in the short term from a list of viable candidates. The results that emerge can provide general guidance on priorities and decision makers can finalize project selections considering this information, additional practical constraints, and other information. The tools and approaches described here present a variant of this approach, incorporating consideration of the performance achieved by a selected set of projects. Appendix E presents a mathematical formulation which theoretically yields a strictly optimal set of projects for implementation by the intrepid.

4.3 Process for Evaluating and Prioritizing Transit Asset Rehabilitation and Replacement

This section describes the seven essential steps in evaluating and prioritizing transit asset rehabilitation and replacement

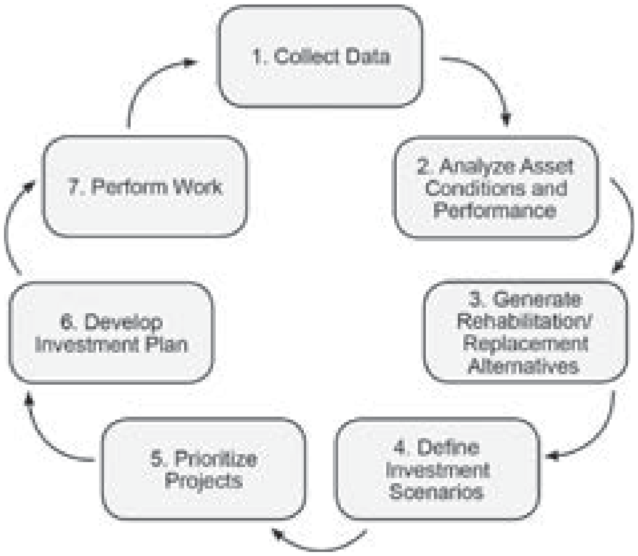
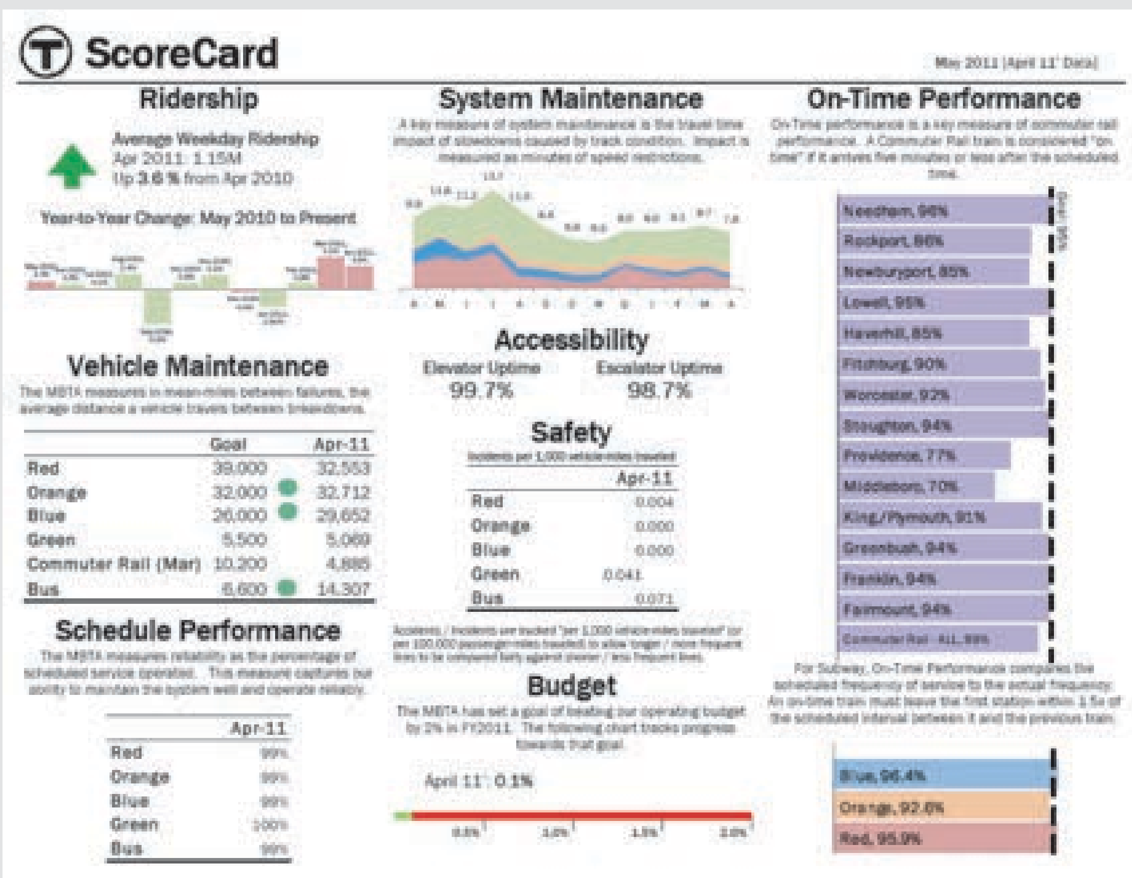


Figure 4-3. Evaluating and prioritizing rehabilitation and replacement projects.

projects. Figure 4-3 illustrates these steps; Figures 4-4 through 4-8 provide illustrative examples of transit agency practices and tools that support the process. The process starts with collecting data on the condition and performance of existing transit assets. This information is analyzed to determine how well the system is performing and what rehabilitation and replacement work may be required. Next, specific project alternatives are generated to address rehabilitation and replacement needs. A set of scenarios is defined to test different prioritization approaches and refine the set of alternative projects. Based on the refined set of project alternatives, the next step is to prioritize specific projects. An asset management or capital plan is then developed that details the selected projects. Over time the work described in the plan is performed, and information on the resulting changes in conditions and performance is captured in subsequent updates of the process. Each of these steps is described in the following paragraphs.

The MBTA has established a one-page scorecard for use in reporting asset conditions. The scorecard includes summary measures of: ridership; mean distance between failures (MDBF); service reliability; minutes of speed restrictions; elevator and escalator uptime; safety adherence to budget; and on-time performance. The scorecard is accompanied by additional details by mode, and is updated on the MBTA Web site on a monthly basis.



Source: MBTA

Figure 4-4. Example of MBTA performance measure reporting.

The MTC uses the Regional Transit Capital Inventory (RTCI) to support analysis of asset replacement needs for Bay area transportation agencies. Phase I of the RCTI established a taxonomy for transit assets and included a needs analysis tool. The tool identified asset replacement alternatives using estimated asset age and industry average life spans for each asset class based upon reports from the agencies and manufacturers. Assumed asset lives are shown at right.

The RTCI serves as the basis for projecting the cost of transit service into the Regional Transportation Plan (RTP), the 25-year transportation funding allocation plan for the nine counties in the San Francisco Bay Area. The RTP estimates funding needs to maintain transit assets for each transit agency according to three different scenarios on the Average Age of Assets as a Percentage of their Useful Life (AAAPUL), a measure that reflects overall asset conditions and goals to achieve state of good repair.

Assumed Useful Life of Assets

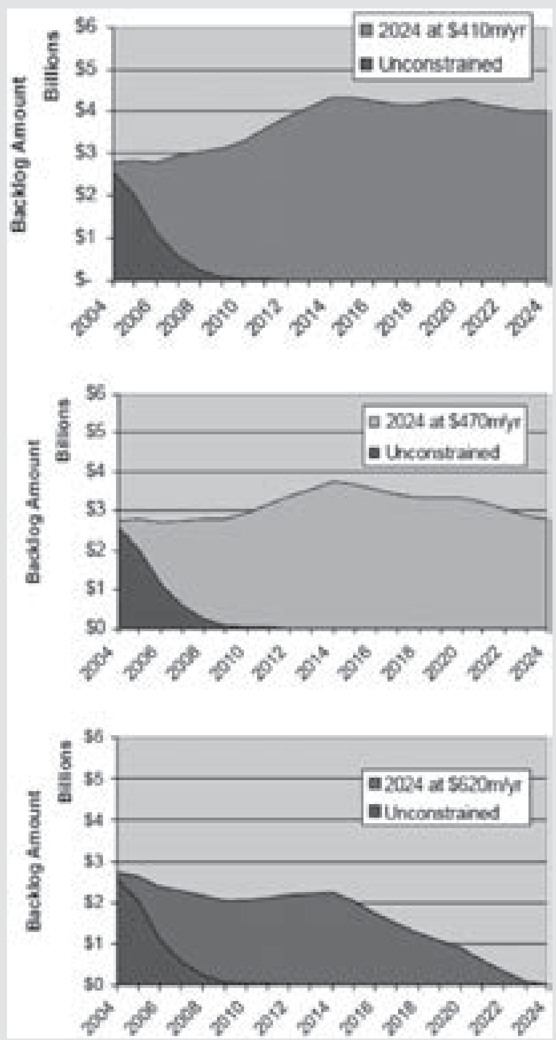
Asset Type	Asset Life (yrs)
Over-the-road coaches	14*
Other heavy-duty buses	12*
Medium-duty buses	10*
Vans	4-7
Light rail vehicles	25
Trolleys	15
Heavy rail cars	25**
Locomotives	
Heavy/steel hull ferries	30
Light weight/aluminum hull ferries	25
Used vehicles	varies by type
Tools and equipment	10
Service vehicle	7
Non-revenue vehicle	
Track	varies by type
Trolley overhead/third rail	
Facility	

*may be extended 5 years if rehabilitated
**may be extended 20 years if rehabilitated

Figure 4-5. Example of MTC regional transit capital inventory.

Since passage of "Forward Funding" legislation in 2000, the MBTA has been required to prepare an annual Capital Investment Program (CIP), a rolling 5-year constrained investment plan, and use state of good repair as a criterion for the inclusion of projects in the CIP. To meet this requirement, the MBTA developed a Microsoft Access State of Good Repair database that has an inventory of its assets and approach for predicting future asset replacement needs based on expected asset lives.

The MBTA uses its database to analyze asset rehabilitation/replacement needs and prioritize allocation of funds given a budget constraint. To use the system, the MBTA defines candidate asset rehabilitation and replacement projects. For each candidate, three basic measures are quantified: the age of the asset as a percent of its useful life, operational impact of the candidate project, and cost effectiveness of the project (ridership impacted divided by the cost of the action). The system then simulates candidate projects over time given a budget constraint and prioritizes what projects to perform given user-specified weights on the three factors.



Source: MBTA

Figure 4-6. Example of MBTA state of good repair database.

The MTC worked cooperatively with Bay area cities, counties and transit operators to determine the process to be used during the evaluation of transit projects for inclusion in its Transportation Improvement Plan (TIP) and for programming of FTA Section 5307 and 5309 Fixed Guideway funding.

The MTC adopted the results as Resolution Number 3908. It calls for operators to submit capital projects/programs with approval from their boards, whereupon they are screened, scored, and selected. The projects are screened for consistency with the plans of the operators' neighbors, the MTC's 25-year Regional Transportation Plan, and the operators' own plans. The operators must also confirm that the project/program has adequate cash flow, clear project limits, a defined scope of work, and project readiness.

The projects that pass through screening are then scored according to their project category using the scores shown at right. For asset replacement projects, project category descriptions prescribe the age of an asset to be replaced, characteristics of the new asset, and purpose of the asset. The highest scoring capital projects are assigned to a fund source and apportioned funding for the urbanized area in which the operators are the claimants.

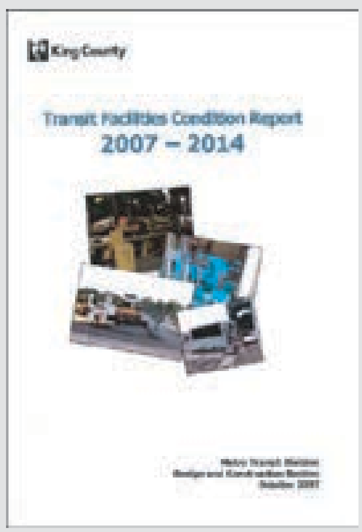
MTC Project Scores

Project Type	Score
Revenue vehicle replacement or rehabilitation	16
Used vehicle replacement	
Fixed guideway replacement or rehabilitation	
Ferry propulsion, major component or fixed guideway connectors	
Revenue vehicle communication	
Fare collection/farebox (including Translink system)	
Bus diesel emissions reduction	
Safety	15
ADA/non-vehicle access improvement	14
Fixed/heavy equipment, maintenance/operating facilities	13
Stations/intermodal stations/parking rehabilitation	12
Service vehicles	11
Tools and equipment	10
Office equipment	9
Preventive maintenance	
Operations/operational improvement enhancements	8
Expansion	

Figure 4-7. Example of MTC project prioritization.

King County Metro established the Transit Asset Management Program (TAMP) for managing its fixed assets. The TAMP addresses investment needs for facilities and infrastructure, as well as for equipment and asset replacement. Assets that are within six years of requiring replacement or rehabilitation are inspected on a yearly basis.

The TAMP team develops an annual work plan based on these inspections, the available budget, and other factors. Summary information on King County Metro's fixed assets is provided in the *Transit Facilities Condition Report*.



Source: King County Metro

Figure 4-8. Example of the King County Metro Transit Asset Management Program.

Step 1: Collect Data

The process of evaluating and prioritizing rehabilitation and replacement work starts with collecting data on existing transit capital assets. Data are needed to describe the transit agency's asset inventory and to establish the condition of the inventory as an initial step in determining what rehabilitation and replacement actions may be needed. As with the final step of the process, *performing work,* the issue of data collection is a complex one that extends beyond the realm of rehabilitation and replacement analysis that is the focus of this report. The topic of data collection is detailed in *TCRP Report 5: Guidelines for Development of Public Transportation Facilities and Equipment Management Systems (4),* as well as in the IIMM (*2*) and PAS 55 specification (*3*). The reader is referred to these resources for detailed discussions of resource requirements for data collection, what data are required on existing assets to support an asset management approach, and how to design a data collection program. These resources provide significant additional detail on the substeps summarized below for supporting rehabilitation and replacement decisions.

Establish the capital asset inventory. Collecting asset data starts with quantifying the set of existing capital assets. Transit agencies may choose to reference an existing asset classification system (e.g., TERM Lite) as a guide for establishing or enhancing a capital asset inventory. The guidelines for NTD reporting can also serve as a foundation for these efforts by providing a de facto minimum set of standards for describing a transit asset inventory. However, the information collected by the NTD is fairly limited. Transit agencies need much more data on their assets and at a finer level of detail to support activities such as day-to-day maintenance and decisions on capital rehabilitation and replacement projects. For buses, data are typically retained at the level of the individual bus (rather than at the fleet level provided in the NTD), and include information on the maintenance history of the bus, causes of any breakdowns, and inspection results. In the case of rail, vehicles are generally further broken down by major subsystem: propulsion, brakes, car body, interior, and so forth. Tracking at the subsystem level is important when there are significant differences in asset life such that component-level information is needed to describe rehabilitation and replacement actions. Component/subcomponent level data also are important for guideway, structures, and facilities.

Define data collection and inspection protocols. Once a transit agency has established its capital asset inventory, it is important to establish the protocols for keeping the inventory updated and for collecting data on asset conditions. A variety of approaches are used for different capital assets, including periodic or mileage-based inspections (for vehicles), use of automated data collections (such as track geometry cars for rail inspection), statistical sampling, and customer surveying. Generally speaking, the data requirements for supporting asset maintenance are the controlling factor in determining what data are collected. Supporting rehabilitation and replacement decisions requires that data on asset conditions are detailed and current enough to support determining what assets require rehabilitation or replacement. In cases where resource constraints preclude the collection of asset condition data, condition may need to be inferred through age-based modeling. However, when information on the asset is limited to its age and no additional data are available to support remaining life or probability of asset failure/breakdown, it can be difficult for the transit agency to analyze its needs. Thus, some description of the asset's condition is recommended to supplement data on its age. Updates to inventory and condition data should be made corresponding to analysis of rehabilitation and replacement needs (typically conducted annually), unless data are collected more frequently to support maintenance decisions.

Implement an asset management system. While it is not necessary for a transit agency to implement a computerized asset management system to support the framework described here, as a practical matter such a system is extremely helpful for all but the smallest of capital asset inventories. Existing asset management systems are used to store inventory and condition data, as well as to support maintenance tracking and decisions. Asset management systems can be used to support rehabilitation and replacement decisions, though the commercial off the shelf (COTS) systems that demonstrate such decision support capabilities typically are tailored to support analysis of specific asset types, such as highway pavements or bridges. Regardless, asset management systems are useful for storing the data required for rehabilitation and replacement analysis, regardless of whether the analysis is in fact performed in those systems or externally. As in the case of establishing data collection and inspection protocols, it is generally the needs for asset maintenance that drive the decision of what, if any, asset management system to implement. If a transit agency has not implemented a full-featured asset management system, basic asset inventory and inspection data can be stored in spreadsheet format.

Step 2: Analyze Asset Conditions and Performance

This step uses data on existing transit assets to assess how well these assets are performing and to project future condition and performance. It assesses potential future conditions that are then used to determine when rehabilitation or replacement of an asset is needed and what rehabilitation or replacement alternatives exist. The analysis utilizes performance measures, relating the measures to condition data and projecting condition and performance, as described below.

Define performance measures. The decision of what measures the transit agency should use to characterize asset performance is critical and can be made prior to or in conjunction with efforts to collect asset data. Characterizing performance of existing assets should be seen as one aspect of a transit agency's overall performance management program. Efforts to define performance measures to use for existing assets ideally should be conducted as part of a large effort to define performance measures for the transit agency as a whole. Table 4-1 recommends a set of core measures for use in supporting asset rehabilitation and replacement decisions. A transit agency may have additional measures not shown in the table that would be desirable to calculate to support decision making, but that may be difficult to quantify without additional data collection. The table was developed based on the following strategy:

- Performance measures should be defined for all physical assets. At a minimum, assets should be characterized based on their condition on a good/fair/poor scale, where an asset in poor condition is one that is at or near the end of its service life, requires immediate rehabilitation or replacement, or is deemed to be in poor condition based on inspection. Use of a good/fair/poor scale has several advantages: it simplifies reporting, allows for aggregation of assets across types, and allows for combining different condition scales.
- Transit agency costs should be calculated for all assets and user costs should be calculated for assets that can impact service performance. The consequence of failing to maintain an asset is not merely that the asset may deteriorate to a worse condition—it will also drive up future costs. The FTA TERM Lite system has default cost data that can be used as an alternative if a transit agency has limited cost data available.
- Excess hours of delay is recommended as a measure for use in characterizing customer impacts, particularly for vehicles. Using this measure transit agencies can better compare decisions about reinvesting in existing assets to service expansion, and can better compare impacts across fleets with varying service lives and operating characteristics. The tools described in Section 5 calculate hours of delay and convert this measure into user costs.
- Asset availability provides a valuable measure for communicating user impacts for assets such as elevators and escalators, and may be easier to calculate than delay for some assets.
- The percentage of assets enhanced in some fashion (e.g., meeting a standard for low emissions) is recommended as a general approach for capturing other factors, such as environmental performance and accessibility. Another approach for characterizing sustainability benefits for buses is to report

Table 4-1. Minimum set of measures recommended for supporting rehabilitation and replacement decisions.

Measure	Use For	Notes
Percent of assets in good/fair/poor condition	All assets, including facilities	Useful for reporting and analysis. The threshold for poor condition should coincide with the recommended threshold for rehabilitation/ replacement.
Asset availability	All assets excluding those for which availability can be related to delay	Useful for reporting, particularly in cases where it is difficult to relate asset service to delay.
Agency cost	All assets	Useful for analysis. Should include transit agency life cycle maintenance costs, and other costs that vary with asset condition.
User cost	All assets with direct impact on system performance	Useful for analysis. Should include delay costs and other user costs.
Hours of delay	Vehicles, guideway	Useful for analysis and reporting. Hours can be converted to costs for analysis.
Percent of assets enhanced/improved	All assets	Useful for analysis and reporting. Use to measure extent of improvements to existing asset, such as percent of buses with low emissions or improved technology.

the CO_2 emissions per vehicle mile, which is indicative of societal benefits of lower emissions buses.

- Different measures may be used for analysis and reporting. For instance when analyzing asset condition and needs it may be useful to analyze conditions at a component level, but for reporting purposes it may be preferable to communicate results in terms of high-level measures.

Performance measurement is a complex topic, and extends beyond the area of capital asset rehabilitation and replacement that is the focus of this report. Important considerations in identifying performance measures for supporting transit asset rehabilitation and replacement decisions adapted from *NCHRP Report 551 (15)* are as follows:

- **Feasibility:** a performance measure is useful only if the transit agency can capture the data needed to support its calculation. Measures that require extensive measurement or inspection programs to quantify may be desirable, but fail to meet this criterion. In considering whether to use a given measure, the transit agency must consider the cost of quantifying the measure, and weigh this against the marginal value of having the information the measure would provide. For instance, the most basic information one might obtain about an asset is its age, which can be used to estimate remaining service life given the expected service life by asset type. Having additional information on the actual physical condition of the asset is of additional value, but how much additional value condition data provides depends on how expensive it is to collect condition data, and upon how accurate asset age is in predicting the asset's condition. For assets that are numerous and that deteriorate more or less uniformly with age (e.g., signs), there is little marginal value to obtaining condition data compared to assets that are less numerous, are critical to safety, and for which age may be a poor predictor of condition (e.g., structures).
- **Policy sensitivity:** performance measures used to support resource allocation decisions should ideally relate to transit agency policy objectives and should provide a measure of whether the expected outcomes of policy objectives are occurring. This tends to emphasize measures correlated with transit service from the transit customer's viewpoint. For instance, on-time performance is more meaningful for a typical passenger than a condition score. Likewise, the availability of elevators or escalators in stations is more meaningful than average asset age.
- **Long-term view:** to support rehabilitation and replacement decisions it is important to leverage information on trends in performance and predictions of future performance given a set of budget assumptions. Also, it should be possible to predict performance of the selected measures over the entire life cycle of an asset. In other words, it should be possible to graph the selected measures over time and over the life of an asset. If a measure cannot be predicted in the future, then it may be of value for reporting or tracking purposes, but it will not be an effective measure for supporting asset replacement decisions that rely on predicting future performance.
- **Useful for decision support:** this refers to the degree of correlation between a performance measure and decisions about asset rehabilitation and replacement. The ideal measure would be highly correlated with asset-level decisions. That is, the measure would provide information on when rehabilitation or replacement is needed, would be impacted as a result of rehabilitation and replacement actions, would not be unduly impacted by factors outside of the transit agency's control, and would be useful for testing different budget scenarios. Asset age, remaining service life, and condition ratings are commonly used measures that meet these criteria for many assets.
- **Useful across the transit agency:** ideally the performance measures adopted for supporting asset management decisions are measures that are used broadly across the transit agency, such as for reporting across modes or units and to the public. Using measures across the transit agency where feasible helps reduce the total number of measures that must be tracked, simplifies reporting, improves transparency, and strengthens the linkage between asset-level decisions and transit agency goals. However, it is often the case that measures used for asset-level decisions are more technical or are reported at a finer level of detail than is reasonable for reporting across the transit agency.

  For instance, asset age or remaining service life satisfies the need for a measure that is feasible to collect, provides a long term-view, and is useful for decision support (for assets where condition is well-correlated with age). However, this measure is not particularly policy-sensitive and of little use except for supporting rehabilitation and replacement decisions. On the other end of the spectrum, measures such as customer satisfaction are very relevant when considering transit agency policy and extremely valuable for internal communication. But many different factors besides asset condition contribute to customer satisfaction, so this is a poor measure for use in providing a long-term view or supporting decisions on asset rehabilitation and replacement.

Calculate current conditions and performance. Once a set of performance measures have been established, the next step is to use the available data to calculate current conditions and performance. This is a useful calculation in that it helps establish trends for evaluating the impact of investment decisions and provides a baseline value to use for analyses of the cost to maintain or improve current conditions. The calculation is relatively straightforward for measures that can be directly observed or captured through an inspection process.

In such cases the most significant issue is how to aggregate asset or component-level measures for reporting. For condition-based measures, the replacement value of the asset is recommended for use in calculating weighted condition across assets of different types or dimensions. A number of measures cannot be directly observed, but are instead calculated based on condition data.

Project conditions and performance. Data collection efforts provide a view of the conditions of the asset inventory at a point in time that is always in the past. To support development of an investment plan, which by definition is a projection of future events, it is necessary to estimate, or at least make a set of assumptions concerning future conditions. In this step the available data, information on asset deterioration, and models relating conditions and performance are used to predict future conditions and performance in the absence of new rehabilitation and replacement work. This calculation may incorporate previously programmed projects and should consider the rate of asset deterioration. If age is used as the basic measure of condition, then the calculation of deterioration is straightforward, but additional calculations are required to estimate condition based on age. If condition is measured directly, then a deterioration curve is required. The models used previously for calculating other measures from condition, such as delay, can be applied once again to predict future performance.

Step 3: Generate Rehabilitation and Replacement Alternatives

In this step the transit agency determines the set of candidate rehabilitation and replacement alternatives that might be performed depending on available funding. These rehabilitation and replacement actions define what is required for the transit agency to achieve a state of good repair—the condition in which a transit agency performs all maintenance and capital activities on its existing assets required to provide a specified level of service in the most efficient manner consistent with transit agency policy. This process consists of first developing a rehabilitation and replacement policy for each asset, applying the policy to each asset to determine a set of candidate actions, and quantifying the costs and impacts of each action.

Develop a rehabilitation and replacement policy. The rehabilitation and replacement policy specifies what rehabilitation or replacement actions should be performed on each asset viewed in isolation. That is, at what point should the asset be rehabilitated or replaced consistent with transit agency goals, absent specific budget or other constraints? The next section describes basic approaches to determining such a policy. Theoretical models for developing a rehabilitation and replacement policy are instructive and useful for suggesting a starting point for further analysis, but transit agencies must consider additional factors not captured in such models. Often there are additional benefits to replacing an asset, such as improved performance or efficiency, or technological innovations improve some aspect of performance. For complex assets such as rail vehicles or facilities it can be unrealistic to view each asset in isolation; the optimal policy may involve performing a combination of rehabilitation or replacement actions on a set of related assets, such as performing out-of-phase replacement of ballast, ties, fasteners and rail on a fixed guideway. Manufacturer guidance on recommended maintenance and expected life are often important to consider. In addition, existing practices must be accounted for. If current practice is not consistent with a given policy, further analysis may be justified to evaluate why the discrepancy exists, and the policy may be adjusted to better match practice if it is found to be defensible. A transit agency's rehabilitation and replacement policy is the product that results from considering all of these factors.

Determine candidate actions. Developing a defensible rehabilitation and replacement policy for every transit capital asset is no small feat. Fortunately, once the policy has been developed, the next step is less difficult. Armed with information on existing conditions and the rehabilitation/replacement policy, the transit agency should then proceed to apply the policy to its assets to determine what rehabilitation and replacement actions are recommended for its inventory. The set of actions defines the requirements to achieve a state of good repair.

Quantify costs and impacts of each alternative. At this point in the process, nearly all of the information that is needed to proceed with a scenario analysis has been defined. It is necessary to quantify how much the proposed set of actions will cost and what the impacts of taking action would be. For the purpose of analysis, costs specified at this point should be planning-level estimates developed using unit costs that typically would not consider site-specific details for fixed assets or detailed estimates for vehicles. The impact of replacing an asset is at first glance relatively straightforward—the deteriorated asset is replaced with a new one—but if there are performance improvements or other benefits of replacing an asset, these should be identified (and if possible, quantified). The impact of rehabilitating an asset should also be quantified. Typically, rehabilitation will have the effect of extending asset life and reducing user costs (through reducing the number of failures), or at least reducing maintenance costs.

Step 4: Define Investment Scenarios

An investment scenario is a description of a set of potential future events concerning a set of assets and investments. It describes what conditions and performance will result from a set of assumptions concerning asset deterioration, transit agency funding, and priorities for asset rehabilitation and replacement. A scenario "tells a story" about what may happen to the transit agency's assets, depending on decisions about how to invest in those assets. Comparing alternative scenarios is a powerful tool for supporting investment decisions, particularly when a decision maker must contend with significant uncertainty and investment objectives that are difficult to weigh against each other. The process of evaluating investment scenarios requires developing funding and prioritization assumptions, defining the scenarios, and simulating future conditions, described further below. The description focuses on asset rehabilitation and replacement scenarios, but in practice the approach can be extended to compare these investments to other transit agency investments, such as investments in new capacity.

Develop funding and prioritization assumptions. Analyzing a set of investment scenarios requires a set of assumptions regarding funding levels and funding priorities. This presents a chicken-and-egg problem: a set of assumptions is needed, but given that the scenario analysis is supposed to aid in setting funding levels and priorities, these should not be firmly established at this stage. This conundrum can be resolved by conceding that whatever assumptions one develops in this step will be revisited later in the analysis, perhaps triggering the need for a revised set of scenarios in an iterative manner. With this qualification in mind, one can proceed with defining a range of different funding levels that should be considered and developing an approach for prioritizing funds between different needs.

An important consideration at this stage is how funding should be allocated. Ideally, a single overall funding level should be defined for addressing rehabilitation and replacement of transit assets, and the prioritization approach should support allocating funds to assets with the greatest need if available funds are insufficient for addressing all rehabilitation and replacement needs. Another approach is to divide funds according to categories, such as by investment objective or mode. The discussion here assumes that a single funding category (or "bucket") is established for rehabilitation and replacement needs relative to other investments, and these needs compete directly with each other across modes. However, the method described applies equally well with different approaches to dividing funds.

Regardless of the number of funding categories, an approach for each is needed for prioritizing funds. The next section describes this topic in further detail. Typically at this stage one would use a preexisting prioritization approach, if available, or infer a prioritization approach based on current practice at the transit agency.

Defining scenarios. The next step is to determine the exact scenarios that will be evaluated as well as the time frame for analysis. For each scenario it is necessary to determine the funding level by major funding category and the funding strategy that will be used. At least three scenarios are recommended for analysis, including:

- **Achieving a state of good repair:** this scenario involves performing the recommended rehabilitation and replacement actions consistent with transit agency policy to achieve a state of good repair. This scenario is most meaningful if rehabilitation and replacement policies have been established that minimize life cycle costs. In this case, the transit agency can show that over time costs will be minimized if a state of good repair is achieved.
- **Maintaining current conditions and performance:** this scenario describes the funding required to maintain the status quo. As most transit agencies have a backlog of investment needs, maintaining current conditions is generally a less ambitious goal than achieving a state of good repair. However, if the system is new, the status quo may actually be better than the long-term condition would project if the system is maintained in state of good repair. In such cases the analysis should be the same as in the first scenario: assets are assumed to be replaced according to transit agency policy rather than being kept in new condition.
- **Projected future funding:** at least one scenario should estimate the conditions and performance resulting from expected future funds for asset rehabilitation and replacement. Ideally, there would be some flexibility in future funding: the purpose of the analysis is, after all, to establish how funds will be allocated. In other cases, there is not such flexibility and the primary question is how to allocate funds given a known budget.

Additional scenarios may be defined at this point to test alternative funding levels. Also, if there is uncertainty about key factors, such as asset deterioration, ridership, or external events that may impact the system, then different scenarios can be generated to support "what if" analysis.

Simulate future decisions, conditions, and performance. Once the scenarios have been specified it is necessary to quantify what is expected to occur in each scenario. This involves performing the following steps for each scenario over each analysis period (typically each year) of the analysis:

- Calculate current conditions and performance;
- Determine what rehabilitation and replacement work is needed based on the policy;
- Prioritize candidate rehabilitation and replacement actions;
- Simulate allocation of funds;
- Calculate impacts of performing work on conditions and performance;

- Predict changes in conditions occurring over the period for those assets for which no work is performed; and
- Proceed to the next analysis period, carrying forward data on predicted conditions and performance.

The results of this step are predicted expenditures, conditions, and performance for each of the defined scenarios. A decision maker can then use information from the analysis and compare results across scenarios to inform decisions about funding and project prioritization.

Step 5: Prioritize Projects

In this step, the transit agency applies information from previous analysis steps to prioritize potential rehabilitation and replacement projects. This process requires a utility function or project scoring approach to use to prioritize, and a set of projects to which to apply the prioritization approach. The projects prioritized in this step should be projects that are sufficiently well-scoped that they can be included in the transit agency's capital plan. Thus, effort is required at this stage to detail the scope, budget, and timing of the candidate projects identified previously. This may involve combining or splitting rehabilitation and replacement alternatives considered previously in isolation. For instance, one project may include a combination of rehabilitation and replacement actions for multiple asset categories. Once the projects have been prioritized it is important to review the results of the prioritization process, which may require revising the rehabilitation and replacement policy, adjusting performance measures and targets, or revising the scenarios evaluated previously. These steps are described below.

Specify the utility function. A utility function characterizes the value or benefit of a decision, combining economic and non-economic factors. Generally applicable guidelines for developing a utility function to evaluate rehabilitation and replacement projects are as follows:

- Where practical, the utility function should be structured to resemble a calculation of economic benefit, with adjustments to account for factors that are difficult to quantify or cannot be captured with an economic model. This approach lends itself to using economic concepts to prioritize projects, most notably calculating a utility-cost ratio (similar to a benefit-cost ratio) to determine how to allocate funds given a budget constraint.
- The function may include other transit agency objectives that may be impacted by a project and that can be characterized using performance measures. These include capacity expansion, environmental benefits, quality of service or aesthetic benefits from improved or upgraded equipment and facilities, and additional safety benefits.
- Increased maintenance costs required to maintain a target level of safety should be calculated and incorporated in the calculation of transit agency costs.
- The utility function, including weights on objectives, should be carefully documented to ensure the prioritization process is transparent and repeatable.

There are a number of ways to go about specifying a utility function. Given that a utility function is inherently subjective, this process often seems to be more of an art than a science. Perhaps the most subjective and controversial aspect of the process is setting weights on investment objectives. Approaches to estimating objective weights include: a Delphi process in which one asks experts to provide their judgments on appropriate weights, as described in *NCHRP Report 590* (*65*); an Analytical Hierarchy Process in which weights are inferred from multiple decision makers as implemented in the DecisionLens software described in (*49*); or a consensual process in which one calculates the weights that best match a consensus on the preferred set of outcomes, as described in (*69*).

Refine project scope and budgets. The next step is to better characterize the scope, timing and budget of those projects that are most likely to be included in the resulting investment plan. The steps described thus far make a very useful but significant assumption: that once a rehabilitation or replacement need is identified, its cost can be estimated and a project can be implemented in direct response to the need. In reality the process of project development is more complex than this. Projects take time to define and may extend over many years. At this point, projects that may be included in the plan should be specified in sufficient detail based on the transit agency's standards for capital plan development. This typically involves considering project timing, specifying any major project constraints (e.g., acquisition of new vehicles that requires corresponding changes to stations or other facilities), and determining an estimated cost by project phase (design, preconstruction, construction).

Apply the utility function. Finally, the utility function is applied to the list of projects to establish priorities. The order in which projects would be selected, based strictly upon the utility function, can be approximated using either the utility or utility-cost ratio, depending on how the utility function is defined. At this point, the results of the prioritization should be evaluated considering the following questions:

- Are the project priorities consistent with the scenarios defined previously? That is, if the priorities are used to select what work to perform, is the predicted distribution of funds consistent with that modeled in developing the scenarios? If not, then the scenario evaluation should be revised so that its results better match those generated using the prioritization approach.

- Do the resulting priorities match decision makers' expectations concerning how funds should be allocated? There can certainly be cases in which the process yields a result that, though counterintuitive, is strictly preferable to an expected result. However, cases where results differ from expectations merit further analysis and will almost certainly require some detailed explanations.
- Do the conditions and performance predicted given the expected budget allocation (or a range of possible budgets) meet transit agency performance measure targets? If they do not, this may suggest that changes to the prioritization approach are warranted. Alternatively, the transit agency may need to reconsider its goals or performance measure targets if available funds are insufficient for achieving them.
- Are there groups of projects with similar priorities? This is a common outcome when an objective function is used to capture a number of different objectives, but projects tend to focus on a subset of these. It may suggest the need to fine-tune the utility function to better distinguish between projects, or establish a separate funding category for handling similar projects.
- Are certain assets or activities systematically given low priority? Though some projects are clearly more vital than others, one would expect that as an asset nears the end of its useful life the benefits of replacing the asset would be manifest. Consistently low priorities may suggest the need for revising the prioritization approach or that the rehabilitation and replacement policy is generating recommendations for work before an asset is truly at the end of its useful life. If this issue occurs but cannot be easily addressed, a separate funding category or minimum funding level can be established for the affected assets or activities.

Step 6: Develop Investment Plan

The penultimate step in evaluating and prioritizing transit capital asset rehabilitation and replacement is to develop an investment plan reflecting transit agency priorities. The plan describes recommended and planned asset investments by year for a period of at least five years. For transit agencies with a small number of capital projects, the plan may simply be the transit agency's capital plan supplemented with additional information and analysis of its existing assets. For transit agencies with a large number of projects, development of a separate asset management plan is recommended. Regardless of the exact format of the plan, this step involves defining the funding level and constraints, selecting projects, and preparing the written plan.

Define funding level and constraints. Up to this point, the analyses assume a range of different potential budgets or no particular budget constraint. Such an approach helps provide decision makers with information that is not preconditioned on a certain set of funding assumptions. This is particularly prudent given that when scoping potential rehabilitation and replacement projects, the transit agency's capital budget is likely unknown, as is the distribution of available funds between asset rehabilitation and replacement and other types of investments. In this step, then, transit agency decision makers must make difficult decisions about funding distribution between different investment categories.

The determination of overall funding level may be influenced by perceptions of the transit agency's state-of-good-repair needs, but in the short term the overall funding level is often a given based on available federal, state, and local funding, as well as projected farebox revenue. The distribution of assets between investment categories may also be a given, but as much as possible transit agency decision makers should rely on the analyses described in previous steps to establish funding levels based on an assessment of how well a given distribution of funds will achieve transit agency goals and objectives expressed in terms of its performance measures.

In this step it is also necessary to specify any funding and other constraints that may impact project selection. For instance:

- Are certain funds specified for use for certain assets or actions (e.g., bus replacements)?
- Are there certain projects which will need to be "pipelined" either because the transit agency committed to these projects in the previous plan or because a decision on the project has been made externally?
- What capacity constraints need to be considered, such as limits on the amount of work performed at once on a given line, or the number of projects that can be designed simultaneously?
- Are there minimum amounts of funding that should be invested by asset, mode, or administrative or geographic distribution to best utilize existing staff and resources?
- Where is coordination with other stakeholders required, such as state and local agencies or other transit agencies that may impact project timing?
- Do funding constraints systematically exclude certain types of work from consideration because they are ranked low on the list of priorities?
- Are there other political or institutional factors such as legal or environmental mandates that are influencing the distribution of funds or the selection of projects?

Select projects. Next, a set of decision makers entrusted with finalizing the investment plan must select the set of rehabilitation and replacement projects to include in the plan. They will consider the funding levels that have been established and any constraints on how those funds may be used. If there are few complicating constraints, the project prioritization approach is fully specified, and funding levels are generally adequate, then selecting the set of projects may be as simple as marching through the list of alternative projects in decreasing order of utility/cost ratio, and selecting projects until the budget is expended. In practice, the problem is not so well-specified, there is a great deal of missing or incomplete data, and constraints and complicating factors tend to defy application of systematic approaches.

For these reasons the decision makers who must finalize the investment plan generally have their work cut out for them as they balance competing objectives and constraints and attempt to find a plan that is both feasible and that best meets the transit agency's goals and objectives. The priorities suggested through the previous steps, and the results of any models used to recommend specific projects, provide valuable input, but the final decision of what projects to include in the plan is made with additional factors not captured in the prioritization formula and models.

Prepare the plan. Once the set of projects to include in the plan has been specified, the capital asset and rehabilitation plan itself can be finalized. The plan documents the results of the analysis in terms of what specific actions are recommended or planned, as well as details *why* funds are needed for asset rehabilitation, *how* available funds should be distributed, and *what* the planned investments will accomplish. It thus forms an action plan and serves as a tool for galvanizing support for needed investments. A number of recent asset management guides and reports have described the need for developing asset management investment plans. Volume 2 of the *AASHTO Transportation Asset Management Guide* (*11*) discusses how to develop such a plan and presents several examples of plans that transit agencies have developed. At a minimum, the plan should include sections describing:

- Asset inventory and condition;
- Performance measures and targets;
- Projected funding;
- Investment required to achieve a state of good repair; and
- Planned investments.

In addition, depending on the exact nature of the plan and how it relates to other documents, the plan may include additional sections describing transit agency goals and objectives, long-term projections of needs and demands on the system, risk management, and other topics. The plan should address investments at least five years in the future, though projections 10 to 20 years in the future are often valuable given the long life of many transit assets and the timelines for project development.

Step 7: Perform Work

The final step in the process is to perform the work described in the capital asset and rehabilitation plan. The issues involved in performing the work detailed in an investment plan are at least as numerous and significant as those involved in developing the plan. However, these issues tend to be general issues in project design, development and construction and are addressed in detail in other resources. Areas of particular importance to determine projects to rehabilitate and replace existing assets include: evaluating the most efficient means of project delivery; minimizing schedule and budget overruns; managing cases where further investigation during design leads to rescoping a project (particularly for rehabilitation of facilities and other complex assets); bundling of related rehabilitation actions; and staging projects to address interdependencies between different assets and minimize construction impacts.

Following completion of a project it is important to capture updated asset inventory and condition data either through the regular data collection process or supplemental efforts. As the process is repeated it is important to validate the process for collecting inventory and condition data and any models for predicting asset deterioration. It is also possible, although uncommon, to compare actual conditions and performance resulting from the work detailed in an investment plan to that which was previously projected. Such an analysis can help improve the capital asset and rehabilitation process and the accuracy of the results moving forward.

4.4 Summary

The framework described here addresses the full set of steps required to evaluate and prioritize transit asset rehabilitation and replacement alternatives. Though a transit agency's challenge in maintaining its system in a state of good repair is a continuing one, the process is defined to start with assessing asset conditions and performance and defining a set of performance measures. For each asset type it is necessary to establish what policy should be followed for performing rehabilitation and replacement work and then define what alternatives are available for performing needed work. Use of scenario analysis is recommended to compare different possible rehabilitation and replacement alternatives across asset types in terms of the performance resulting from each scenario. This information is used to determine the allocation of funds for asset rehabilitation and replacement. Once this allocation is established, a transit agency can select projects that best achieve the transit agency's goals, develop a plan detailing the selected projects and resulting conditions, and implement the plan.

The framework for prioritizing transit asset rehabilitation and replacement is a greatly simplified rendition of the complicated set of decisions transit agencies must make on a daily basis about how to best operate and maintain their assets. While it necessarily, and conveniently, omits many of the subtleties and nuances of the decision-making process, these omissions are made in the interest of focusing on key elements related to decisions on asset rehabilitation and replacement. The examples show how three agencies have tailored their decision-making processes to make more effective rehabilitation and replacement decisions, and in so doing, help achieve a state of good repair.

SECTION 5

Tools and Approaches

5.1 Introduction

This section describes tools and approaches for applying the framework described in Section 4 to evaluating rehabilitation and replacement for specific types of transit assets. Section 5.2 summarizes the recommended analytical approach to prioritize rehabilitation and replacement alternatives and evaluating rehabilitation and replacement of existing transit assets, with guidance on models for specific asset types. Section 5.3 describes a set of supporting tools that demonstrate the recommended approach. Section 5.4 provides a detailed example of how the tools can be used to support the framework.

5.2 Recommended Analytical Approach

The analytical approach recommended for supporting the framework described in Section 4 consists of two basic components that are depicted in Figure 5-1. Fundamentally the framework is concerned with prioritizing rehabilitation and replacement of existing transit assets. The prioritization model supports this function. It uses information on specific asset rehabilitation and replacement alternatives, together with information on the available budget, to prioritize rehabilitation and replacement alternatives across asset types to simulate what work will be performed based on the prioritization and available funds.

A complementary set of models has been developed to evaluate asset-specific rehabilitation and replacement alternatives. These models provide guidance on when to perform rehabilitation or replacement actions, calculate the economic benefits of rehabilitation and replacement, and calculate a prioritization index (PI) that is used in the prioritization model to select the set of alternatives to maximize benefits. The vehicle model is used to evaluate the need for replacing buses or rail vehicles. It projects transit agency and user costs of purchasing and operating a vehicle over its lifetime and considers how costs, particularly maintenance and delay costs, increase as a vehicle ages. Use of the vehicle model requires operating information comparable to that required for NTD reporting.

For assets other than vehicles, two approaches have been developed. The age-based model projects the need for asset replacement based upon the age of the asset. It calculates the cost of asset replacement and maintenance and considers the likelihood that an asset will fail if it is not replaced. Note that failure in this context is not necessarily the outright failure of an asset, but denotes a condition severe enough to require immediate replacement of the asset to avoid compromising safety. The condition-based model projects the need for asset rehabilitation or replacement based upon the condition of the asset rather than its age. Like the age-based model, it calculates the cost of different actions that may be performed on an asset and considers the likelihood of asset failure. It also determines what actions should be taken to minimize transit agency and user costs over time. Further, it calculates the additional costs that will be incurred if recommended actions are deferred.

Default age-based and condition-based models have been developed for a range of assets (other than vehicles) using data on asset deterioration extracted from FTA's TERM Lite. Alternatively, a transit agency with sufficient data can develop its own age- or condition-based models. The condition-based model provides more information than the age-based model (in that it recommends a set of optimal actions and considers additional actions besides replacement) and is preferable for complex assets where age may be a poor predictor of asset condition. However, the age-based model requires less data to use. The determination of whether to use the age- or condition-based model for a particular asset should be made considering what data a transit agency has available.

The following paragraphs further detail key assumptions, inputs, and results from the prioritization and asset rehabilitation and replacement models. Appendix E has additional detail on the mathematical formulae behind these models.

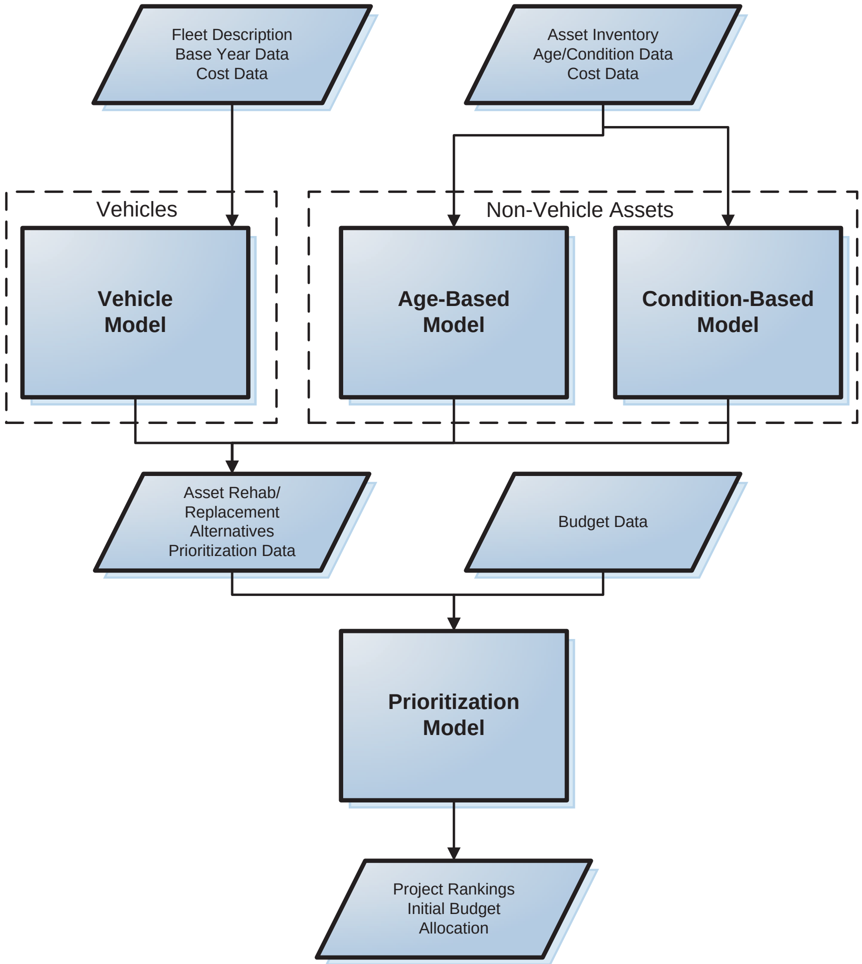


Figure 5-1. Models supporting the asset rehabilitation and replacement framework.

5.2.1 Prioritization Model

The objective of the prioritization model is to recommend a set of rehabilitation and replacement alternatives to perform to maximize utility. Section 4 discusses the concept of a utility function and addresses the objectives one might include in a utility function for evaluating transit asset rehabilitation and replacement. The utility function for rehabilitation and replacement should, at a minimum, include economic benefits of performing a recommended action relative to deferring action for one decision period (typically one year). If economic benefits alone are used in the function, then utility is equal to economic benefit and the solution that maximizes utility will also be the solution that minimizes the sum of life cycle transit agency and user costs. Often an investment will have other benefits that cannot easily be monetized, either for lack of data or because they are non-economic in nature.

The basic problem a transit agency faces in allocating a fixed budget to a set of capital projects is termed the Capital Budgeting Problem. This well-known operations research problem was first formally expressed in 1963 *(76)*. The objective of the problem is to select the set of projects to perform given a budget constraint and goal of maximizing return. Though the objective was initially conceived as maximizing net present value (NPV), one can generalize this objective to maximizing utility. Obtaining an exact solution to this problem requires solving an integer program and can be computationally intensive. This approach is described further in Appendix E. Fortunately, an approximate solution to the problem can be obtained by calculating the benefit-cost ratio (BCR) of the project and the ratio of the net benefits of the project to its initial cost, and then prioritizing projects in decreasing order of this ratio. The tool described in the next section employs this approach.

Note that the term *prioritization index* (PI) is used here to describe the ratio of net benefits to costs, rather than BCR. This term is used to for two reasons. First, the benefits that are calculated using the analytical approach described here are not directly comparable to the benefits one would calculate if performing a typical benefit-cost analysis in which one compares the alternative of performing a project to not performing a project. Because the benefits that are calculated are 1-year benefits of performing needed work relative to deferring action, any alternative with positive benefit (and thus, any non-zero value of PI) is economically justified, whereas common practice in benefit cost analysis is to define the BCR such that projects with a BCR greater than one are economically justified. Second, if other non-economic terms are added to the utility function, then the ratio is technically a utility-cost ratio rather than a BCR.

5.2.2 Asset Rehabilitation and Replacement Models

Three basic approaches have been developed for modeling asset rehabilitation and replacement: a vehicle model that can be applied to buses or rail vehicles; a general approach for modeling other assets besides vehicles for which rehabilitation and replacement needs can best be predicted based on age; and a general approach for modeling assets beside vehicles for which rehabilitation/replacement needs can best be predicted based on condition. Each approach supports predicting the performance of the asset, establishing a rehabilitation and replacement policy, and defining rehabilitation and replacement alternatives. In all cases it is recommended that the rehabilitation/replacement policy be developed considering asset life cycle costs (including both transit agency and user costs), though other considerations can be introduced in prioritization. The following paragraphs summarize the three approaches.

5.2.3 Vehicle Model

The recommended approach for modeling vehicles is adapted from the FTA publication *Useful Life of Transit Buses and Vans (55),* with modifications to extend the approach to rail vehicles. The FTA report details a comprehensive analysis and economic model of bus and van life. Basic assumptions concerning the analytical approach adapted from this report are as follows:

- Vehicles deteriorate primarily as a function of accumulated mileage, which can be approximated by age if one assumes a constant annual mileage.
- Transit agency costs—including rehabilitation, energy, and maintenance costs—all increase as a function of accumulated mileage (and thus, as a function of age). In addition, the probability of breakdowns (called "road calls" for buses and "failures" for rail) increases with accumulated mileage.
- For buses, the primary user cost component that changes as a vehicles ages is the user cost of delay from road calls.
- Practices for bus rehabilitation vary between agencies. However, a common practice is to schedule rehabilitation of specific bus components (e.g., brakes, transmission) based on component lives. Thus, in the model, rehabilitation is represented as a cost that varies based on accumulated mileage rather than as a single, discrete action. It is difficult to generalize rehabilitation practice for rail vehicles, and thus no such adjustment is made.

Based on these assumptions one can predict the accumulated costs of maintaining a vehicle as its mileage increases and can determine when to replace the vehicle given the objective of minimizing life cycle costs. The life cycle cost of a vehicle can be expressed as a function of the purchase cost and the costs of rehabilitation, energy, maintenance, and delay over the life of the vehicle. When a vehicle is replaced, the transit agency pays its purchase cost, but will then incur lower rehabilitation, energy, maintenance, and delay costs and may realize additional benefits from reductions in emissions, improved technology, and/or other factors.

Once a vehicle exceeds its cost-minimizing replacement mileage, a transit agency spends more money to keep the vehicle in service than it would to replace the vehicle. The net benefit of replacing a vehicle can be approximated as the difference between the cost of keeping the vehicle in operation an additional year and the annualized life cycle cost of a new vehicle. This difference represents the net increase in transit agency and user costs that would be incurred by deferring a recommended replacement for one year. This net benefit divided by the replacement cost—the PI—is used to prioritize vehicle replacements in order to minimize a transit agency's costs over time.

The vehicle modeling tools do not consider FTA minimum replacement lifecycles. In practice, as discussed in (*55*), the cost-minimizing replacement age can be expected to be greater than the FTA minimums.

An important qualification concerning rail vehicles relative to buses is that there are more possible rehabilitation strategies, as well as a number of complicating factors regarding replacement of rail vehicles. The approach described in this report presents an approach to calculation of the annualized cost of rail vehicles, but this calculation may be a starting point a transit agency should use in evaluating different rehabilitation and replacement alternatives.

Information required to use the vehicle model includes data on average accumulated mileage per vehicle and base year operating statistics. Model coefficients that predict how different costs increase as a function of accumulated mileage have been based on analysis of nationwide NTD data, as described in Appendix E.

5.2.4 Age-Based Asset Model

The age-based model is intended for use in prioritizing replacement actions for assets other than vehicles that replacement can best be predicted based on asset age. The model predicts the probability of asset failure using a Weibull distribution. This distribution defines the survival curve that shows the probability the asset will fail as the asset ages. As failure becomes more likely, the relative benefit of replacing the asset before it reaches a specified age threshold tends to increase.

In order to determine the benefit of replacement in a given year, the model compares the annualized cost of the asset when replaced at a designated age to the cost of keeping the asset in operation an additional year, which results in maintenance costs and possibly in asset failure. A Monte-Carlo simulation is used to determine an average value for the annualized cost of operating the asset. Costs include periodic replacement, maintenance, and transit agency and user failure costs in the event a failure occurs. As in the case of the vehicle model, the benefit of replacement is the difference between the cost of keeping the asset in operation for an additional year and the annualized cost. The PI is calculated as the ratio of this difference to the replacement cost. When the PI value is greater than zero it is more cost effective to replace the asset than to keep it in service.

Default models have been developed for a range of assets using deterioration data from FTA's TERM Lite. To develop a new model for an asset, one must define its two-parameter survival curve and specify the replacement cost of the asset, as well as the ratio of maintenance and failure costs to the replacement cost.

5.2.5 Condition-Based Asset Model

The condition-based model is intended for use in prioritizing rehabilitation or replacement actions for assets other than vehicles that rehabilitation or replacement can best be predicted based on asset condition. This model approximates the condition of an asset using a Markov Decision Process. This approach is commonly used for pavement and bridge management systems and is well-documented in the literature. To apply the approach, it is necessary to define a set of condition states and a set of rehabilitation and replacement actions for each state. For each state there is a "do minimum" action and potentially other rehabilitation and replacement actions. It is also necessary to specify the cost for each action and the probability of transition from one state to another given that an action is taken. This transition probability matrix thus specifies predicted deterioration (the probability of transition given the "do minimum" action is performed) and action effectiveness. Once a Markov Decision Process has been defined, a linear program can be formulated and solved to determine what actions, if taken on an asset, will minimize costs over time.

The primary output of the model is the recommended rehabilitation and replacement policy that specifies what action to perform based on the condition of the asset. The model also predicts annualized costs assuming the policy is followed, and the future life cycle cost for each condition state/action combination if a given action is performed in the next period, and the optimal policy is followed subsequently. The benefit of performing an action is the savings that will result from performing the action relative to deferring action for one year (performing the "do minimum" action). If this difference is non-zero it is more cost effective to perform the action than to defer work. The PI is calculated by dividing this benefit by the action cost.

Default models have been developed for a range of assets using condition states and deterioration data from FTA's TERM Lite. To develop a new model for an asset, one must define the condition states and actions for the asset, transit agency and user costs associated with each action, and the transition probability matrix for the asset.

5.3 Supporting Tools

A set of four analytical tools have been developed as part of the research effort described in this report. The tools are:

- **Prioritization Modeling Tool:** this tool prioritizes a set of asset rehabilitation or replacement projects, and simulates the allocation of rehabilitation and replacement funds over a 10-year period. To use this tool, one enters an annual budget and a list of projects. For each project it is necessary to enter a project description, the project's cost, and prioritization data. The prioritization data may be either a specific value for PI, or the asset age and coefficients of a PI curve (obtained from the other tools). If a curve is used, the tool predicts how PI increases over the 10-year analysis period as the asset ages.
- **Vehicle Modeling Tool:** this tool uses information on a bus or rail vehicle fleet to estimate the cost-minimizing point at which to replace a vehicle, as well as to predict the priority for replacing the vehicles in a fleet as a function of age. The model considers transit agency rehabilitation and replacement costs, energy or fuel costs, user costs of delay resulting from road calls (for buses) or failures (for rail), and potential savings a transit agency may obtain from new vehicles. The calculations are fleet-specific, allowing for a transit agency to develop different models for different vehicle types. The model considers the fact that certain costs—including rehabilitation costs, energy/fuel costs, and delay costs—tend to increase as vehicles age and accumulate mileage.

- **Age-Based Modeling Tool:** this tool uses information on how an asset (other than a vehicle) deteriorates over time and the target replacement cycle for the asset to predict the annualized transit agency and user costs of the asset, as well as the priority of asset replacement as a function of age. Deterioration models have been derived for a range of asset types from FTA's TERM Lite. Vehicles are not modeled using the tool (as the vehicle modeling tool is recommended for this purpose), but other guideway, facilities, system, and station assets are included.
- **Condition-Based Modeling Tool:** this tool uses information on asset (other than a vehicle) deterioration to predict the annualized transit agency and user costs of the asset, the recommended replacement or rehabilitation action to perform on the asset depending on its condition, and the priority of each action. The modeling approach can be used for any asset that deteriorates as a function of condition. Deterioration models have been derived for a range of asset types from FTA's TERM Lite. Vehicles are not modeled using the tool (as the vehicle modeling tool is recommended for this purpose), but other guideway, facilities, system, and station assets are included.

Note that the same assets are listed in the age-based and condition-based tools. The decision of whether one should use the age-based or condition-based model for a given asset should be based on what data one has available. If one has both condition and age data available, the condition-based model is preferable, particularly for complex assets for which age may be a poor predictor of an asset's condition.

The following sections describe how to use each of the tools. These general guidelines apply consistently across the tools:

- Each tool is implemented as a Microsoft Excel spreadsheet. ***To use the tools one must have Microsoft Excel version 2007 or greater installed and must enable macros. Further, the condition-based modeling tool requires that the Excel Solver be installed.***
- The user should edit values in the white-shaded cells. Other cells need not be edited and are protected.
- All of the tools have an input page and a results page. Two of the tools, the vehicle modeling tool and condition-based modeling tool, have additional pages with detailed model inputs. Buttons are provided at the right side of the screen for navigating between pages.
- All calculations are performed in constant dollars. Inflation is not factored into the analysis.
- Default models are provided for the age- and condition-based tools. The defaults were derived from FTA's TERM Lite. However, no additional data collection or model verification activities were performed as part of the research project to validate the models derived from TERM.

5.3.1 Prioritization Modeling Tool

The prioritization modeling tool prioritizes rehabilitation and replacement projects and simulates allocation of a budget over a 10-year period. To use the tool one must define the budget by year, and provide information on a set of rehabilitation and replacement projects. Figure 5-2 shows the input page for the tool. Inputs include:

- **Base Year** – start year for the analysis.
- **Allow Budget to Carry Over** – specifies whether unspent funds can be carried from one year to the next.
- **Budget** – specifies total rehabilitation and replacement budget by year.

In addition to these inputs, one must enter the following for each project:

- **ID Number;**
- **Description;**
- **Cost** – note that cost units for projects should be the same as used for the budget (e.g., thousands of dollars);
- **Prioritization Index (PI)** – specifies whether a PI model or PI value is entered. The model or value will typically be copied and pasted from one of the other modeling tools described below;
- **Asset Age** – required if "Enter Model" is selected, as the model predicts PI as a function of age;
- **PI Model Coefficients** – required if "Enter Model" is selected;
- **PI** – specific PI value, used if "Enter PI" is selected; and
- **Pipeline Year** – if entered, this specifies the project will be performed in the specified year regardless of its budget or PI value.

Figure 5-3 shows the results generated by the tool. Two tables are shown in the figure. The top table shows spending by year, and backlog (cost of unfunded projects) at the end of each year. To the right of the table, the graph shows spending and backlog in a graph. The bottom table shows the results by project, including the PI and rank in the base year, the year the project was simulated as occurring, and the PI and rank in the program year. Also shown is the benefit or utility of the project in the program year. It is important to note that this is a net benefit of performing action relative to deferring work one year. Thus, any positive benefit is desirable—it is not expected that this benefit value would equal the cost of the project.

5.3.2 Vehicle Modeling Tool

This tool predicts annual costs, the cost-minimizing replacement age, and prioritization data for transit vehicles. It is intended for use in analyzing a fleet of similar vehicles, so a transit agency would likely need to use the tool multiple times

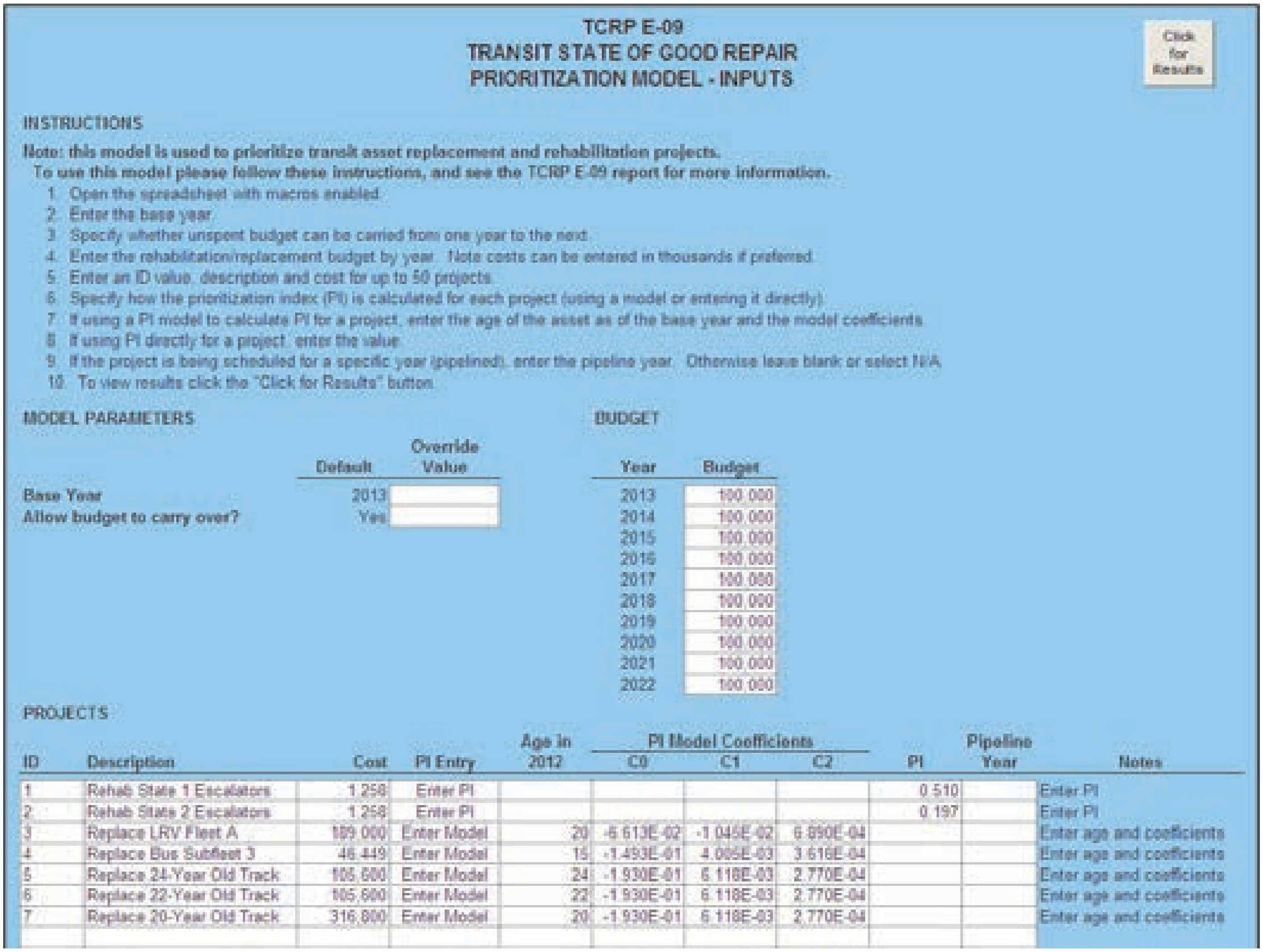
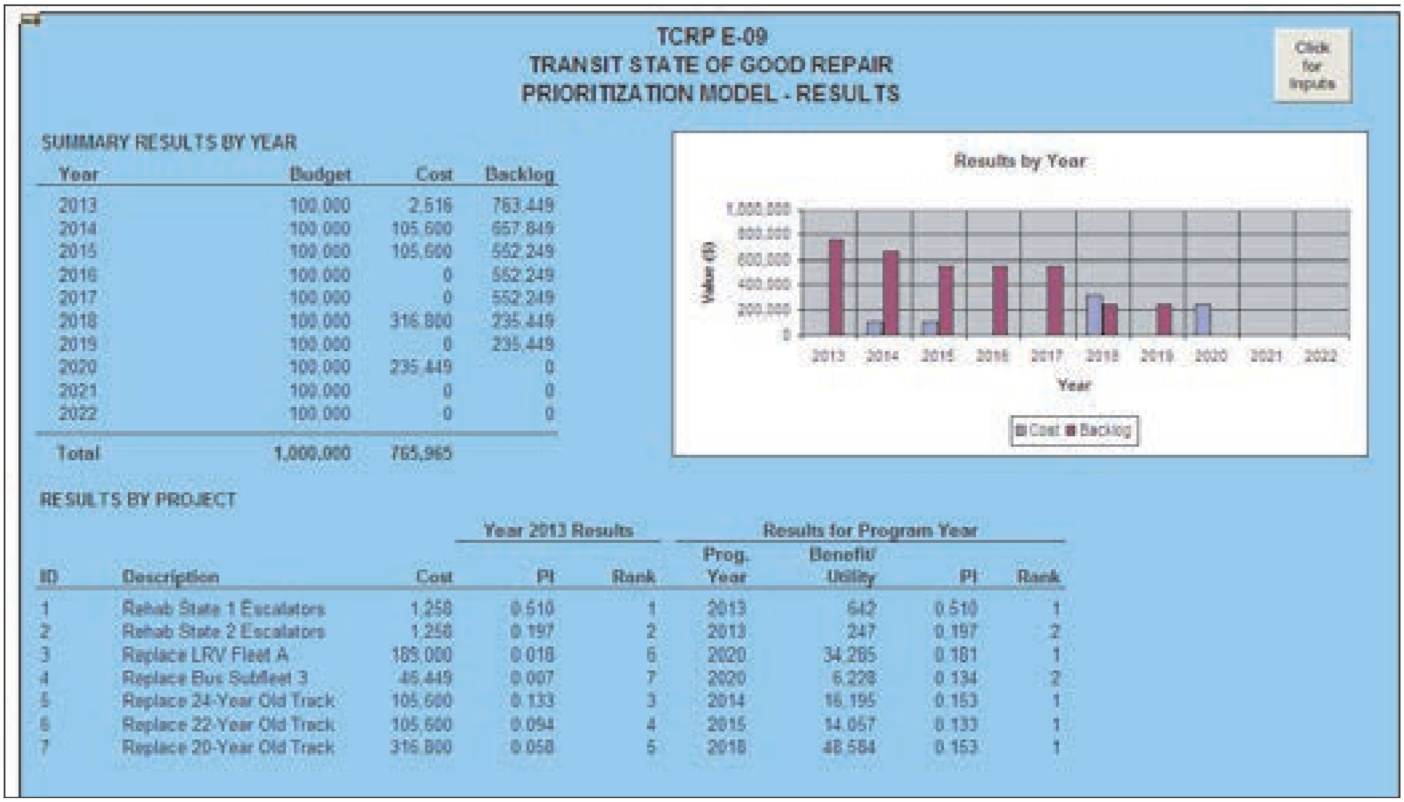


Figure 5-2. Prioritization model inputs.

to model each of its vehicle types. To use the tool, one must describe the inventory and provide a set of base year statistics for the fleet, and one may need to define additional parameters. Figure 5-4 shows the input page for the tool populated with example data. Inputs include:

- **Vehicle Type** – one may select buses, light rail vehicles, heavy rail vehicles, commuter rail vehicles, or user-defined models. Selecting a vehicle type results in selection of detailed model coefficients (shown on the detailed inputs page);
- **Accumulated Mileage and Number of Vehicles** – the user should enter the average accumulated mileage per vehicle and number of vehicles for each subfleet. This may be specified for each of up to 20 subfleets;
- **Base Year** – year for which base year data are provided;
- **Base Year Statistics** – operating information for the vehicle fleet in the based year. Data items are modeled on NTD reporting requirements;
- **New Vehicle Cost;**
- **Other Benefits of Replacement** – additional benefits of a replacement vehicle in dollar per vehicle mile, used to capture benefits such as a improved emission or technology;
- **Passenger Delay Cost** – this is used to calculate the cost of a road call or failure. The default value is the value of time recommended by DOT in 2010 dollars, with a multiplier of four to account for the added inconvenience of unplanned delay. See the project report for additional detail on this parameter;
- **Typical Schedule Headway** – this is used to calculate the cost of a road call or failure. See the project report for additional detail on this parameter;
- **Typical Recovery Time After Road Call/Failure** – this is used to calculate the cost of a road call or failure. See the project report for additional detail on this parameter;
- **Vehicles per Consist** – this is used to calculate the cost of a road call or failure. It should be set to one for buses



Year	Budget	Cost	Backlog
2013	100,000	2,516	763,449
2014	100,000	105,600	657,849
2015	100,000	105,600	552,249
2016	100,000	0	552,249
2017	100,000	0	552,249
2018	100,000	316,800	235,449
2019	100,000	0	235,449
2020	100,000	235,449	0
2021	100,000	0	0
2022	100,000	0	0
Total	1,000,000	765,965	

		Year 2013 Results			Results for Program Year			
ID	Description	Cost	PI	Rank	Prog. Year	Benefit/ Utility	PI	Rank
1	Rehab State 1 Escalators	1,258	0.510	1	2013	642	0.510	1
2	Rehab State 2 Escalators	1,258	0.197	2	2013	247	0.197	2
3	Replace LRV Fleet A	189,000	0.018	6	2020	34,285	0.181	1
4	Replace Bus Subfleet 3	46,449	0.007	7	2020	6,228	0.134	2
5	Replace 24-Year Old Track	105,600	0.133	3	2014	16,195	0.153	1
6	Replace 22-Year Old Track	105,600	0.094	4	2015	14,057	0.133	1
7	Replace 20-Year Old Track	316,800	0.058	5	2018	48,584	0.153	1

Figure 5-3. Prioritization model results.

and the number of vehicles in typical consist or train for rail vehicles; and

- **Discount Rate** – this parameter quantifies the time value of money and should be set according to transit agency policy or left at its default value if the transit agency has not specified a specific value to use for analysis.

In addition to these parameters, one can specify an additional set of detailed parameters. One would not typically set the detailed parameters unless building a new model. Refer to the project report for more information on these parameters.

Figure 5-5 shows the results generated by the tool. These include:

- **Cost-Minimizing Replacement Mileage** – total transit agency and user costs are minimized if the vehicle is replaced at this mileage;
- **Cost-Minimizing Replacement Age** – approximate age at which the cost-minimizing replacement mileage is reached;
- **Average Annual Agency Cost** – average annual cost of the vehicle to the transit agency over its life cycle. This includes the replacement cost, rehabilitation costs, maintenance costs, and energy or fuels costs;
- **Average Annual User Cost** – average annual cost of the vehicle to transit passengers over the vehicle's life cycle. This includes delay costs from road calls or failures;
- **Average Annual Total Cost** – sum of agency and user costs;
- **Prioritization Model Coefficients** – these coefficients predict the PI as a function of vehicle age, describing the curve shown in the graph at the bottom of the screen. The model coefficients should be copied to the prioritization tool; and
- **Sample PI Results** – this is a table showing the PI predicted as a function of age, and is equivalent to the graph shown to the right of the table.

5.3.3 Age-Based Modeling Tool

This tool predicts annual costs and prioritization data for transit assets other than vehicles as a function of asset age. It is intended for use in analyzing a specific asset type, so a transit agency would likely need to use the tool multiple times to model each of its asset types. To use the tool, one must select the asset type and specify a set of parameters for the asset. Figure 5-6 shows the input page for the tool. Required inputs include:

- **Asset Type** – select an asset type from the list, which includes guideway, facility, system and station assets;
- **Unit Agency Replacement Cost** – asset replacement cost specified in the transit agency's preferred units of measure

TCRP E-09
TRANSIT STATE OF GOOD REPAIR
VEHICLE REPLACEMENT MODEL - INPUTS

INSTRUCTIONS

Note: this model is used to predict the average annual cost, the cost-minimizing replacement age, and prioritization data for transit vehicles.

To use this model please follow these instructions, and see the TCRP E-09 report for more information.

1. Open the spreadsheet with macros enabled
2. Select an asset type from the dropdown or select "User-Specified" if developing a new model.
3. Enter accumulated mileage (per vehicle) and number of vehicles for up to 20 subfleets of the same vehicle type.
4. Enter the base year and base year fleet statistics
5. Enter the cost of a new vehicle.
6. If desired enter an estimate of other replacement benefits per vehicle mile (e.g., reduced emissions).
7. If desired enter the delay cost, typical schedule headway, recovery time, vehicles per consist, and/or the discount
8. If desired click the "Click to Edit Details" button to edit additional details (necessary only for a new model)
9. To view results click the "Click for Results" button

Click to Edit Details

Click for Results

REQUIRED INPUTS

Vehicle Type: Bus

Inventory Description:

Group	Accumulated Mileage	Number of Vehicles	Group	Accumulated Mileage	Number of Vehicles
1	147,882	90	11	182,325	6
2	114,252	25	12	212,728	60
3	456,352	117	13	25,063	26
4	298,374	25	14	18,970	54
5	418,483	158	15		
6	246,390	40	16		
7	245,590	60	17		
8	285,708	165	18		
9	272,171	10	19		
10	191,941	39	20		

Base Year Statistics:

	Default	Override Value	Notes
Base Year	2009	2009	
Passenger Miles (000)	1	259,208	
Unlinked Trips (000)	1	58,485	
Vehicle Miles (000)	1	31,006	
Revenue Vehicle Miles (000)	1	23,747	
Revenue Vehicle Hours (000)	1	1,747	
Number of Road Calls (buses) or Failures (rail)	1	4,299	
Energy Cost for Vehicle Operations (000)	1	22,956	
Vehicle Maintenance Cost (000)	1	58,574	

OPTIONAL INPUTS

	Default	Override Value	Notes
New Vehicle Cost ($ per vehicle)	397,000		
Other Benefits of Replacement ($/vehicle mile)	0.00		results in higher benefit for replacement
Passenger Delay Cost ($ per hour)	48.40		
Typical Schedule Headway (min)	30		
Typical Recovery Time After Road Call/Failure (min)	60		
Vehicles per Consist	1		leave blank for buses
Discount Rate (%)	7%		

Figure 5-4. Vehicle model inputs.

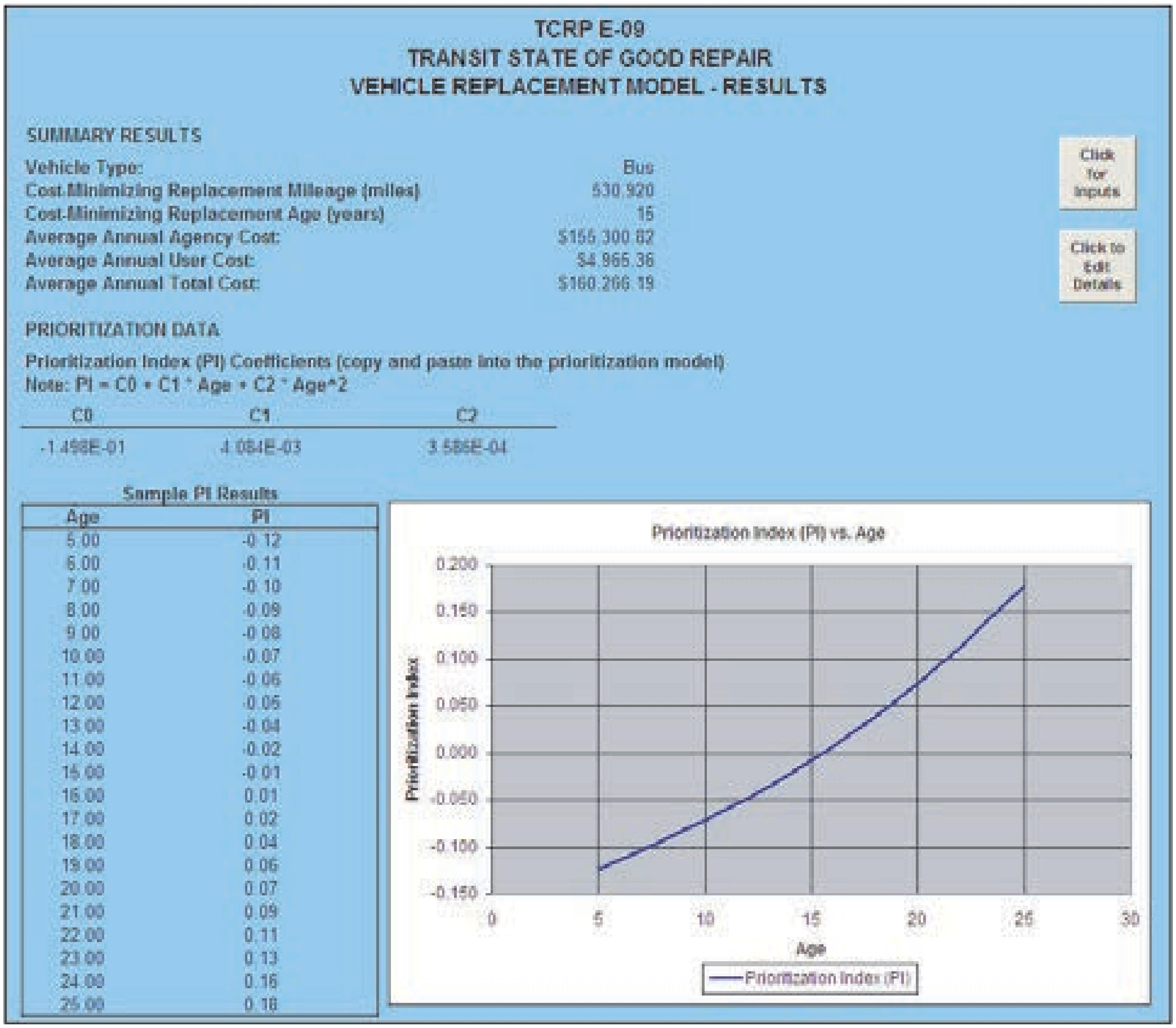


Figure 5-5. Vehicle model results.

for the asset. For instance, facilities or systems would typically be characterized according to cost per asset, while guideway-related costs may be specified in cost per lineal foot or yard; and

- **Assumed Replacement Age** – age at which the asset is assumed to be replaced, used for predicting future costs of an asset. Note that one can experiment with different values for this parameter to determine the cost-minimizing age. Defaults are specified by asset based on values in TERM Lite.

In addition to these parameters, one may optionally specify values for an additional set of parameters, although this is not required unless developing a new model. These include:

- **Unit User Replacement Cost** – user cost of replacement. This parameter can be used to capture costs of delay during asset replacement, or, alternatively, additional benefits of asset replacement to users (through entering a negative number);
- **Annual Maintenance Cost** – annual cost of routine maintenance as a percentage of the replacement cost of the asset, set to 5% by default for all assets;
- **Agency Failure Cost** – cost of asset failure (often the forced replacement of an asset rather which may involve emergency repairs and passenger delay rather than outright failure) to the transit agency, set to 150% of the asset replacement cost by default;
- **User Failure Cost** – cost of asset failure (often the forced replacement of an asset rather which may involve emergency repairs and passenger delay rather than outright failure) to transit users, set to 150% of the asset replacement cost by default;

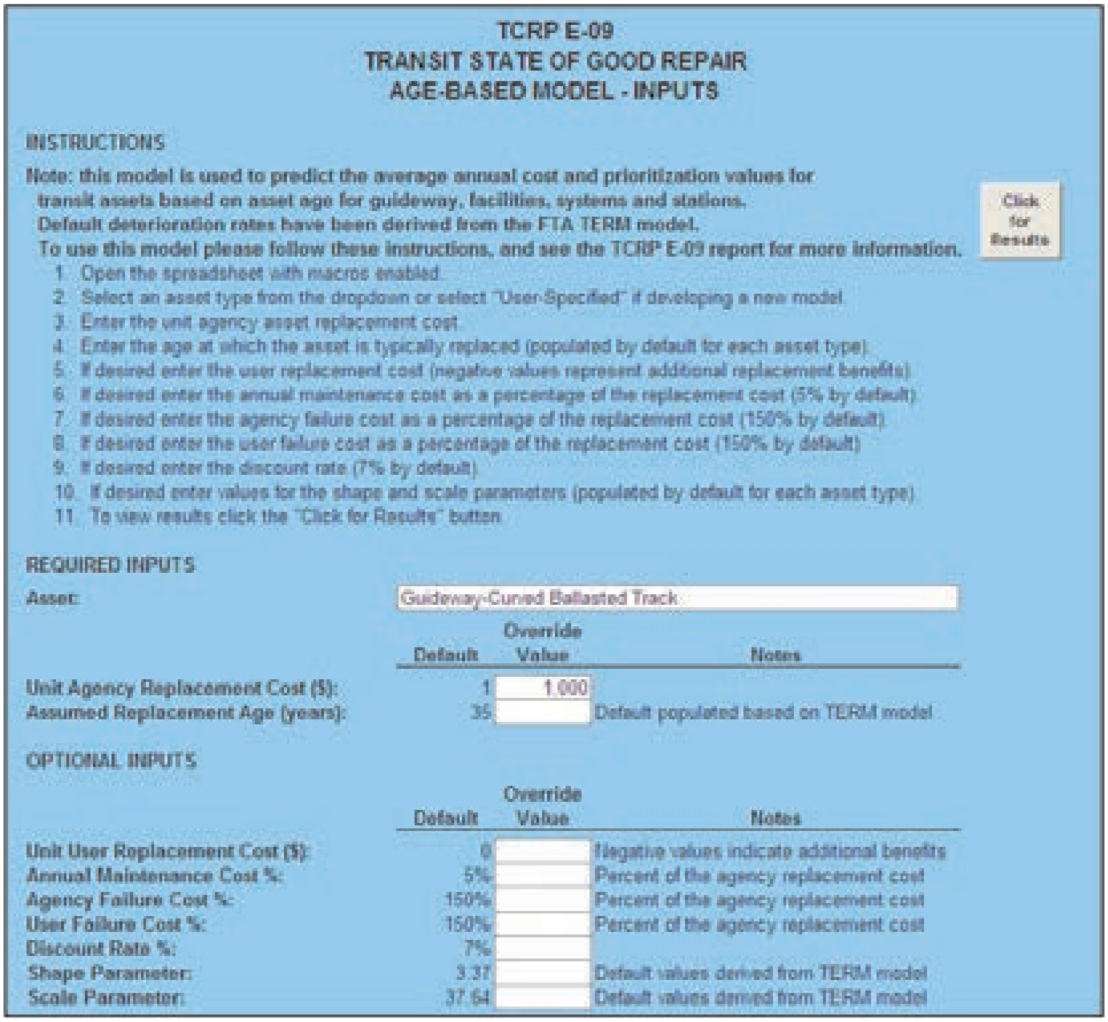


Figure 5-6. Age-based model inputs.

- **Discount Rate** – this parameter quantifies the time value of money and should be set according to agency policy or left at its default value if the transit agency has not specified a specific value to use for analysis;
- **Shape Parameter** – model parameter set by asset type that describes the degree to which the probability of failure changes as a function of age. Values of 1 or greater indicate the asset is more likely to fail as it ages. Refer to Appendix E for additional information; and
- **Scale Parameter** – model parameter set by asset type that specifies the age by which 63% of a set of assets of similar age would be expected to fail. Refer to Appendix E for additional information.

Figure 5-7 shows the results generated by the tool. These include:

- **Average Annual Unit Agency Cost** – average annual unit cost of the vehicle to the transit agency over its life cycle. This includes the replacement cost, maintenance costs, and transit agency failure costs;
- **Average Annual Unit User Cost** – average annual unit cost of the vehicle to transit passengers over the vehicle's life cycle. This includes delay costs from failures and the user replacement cost, if specified;
- **Average Annual Unit Total Cost** – sum of agency and user costs;
- **Prioritization Model Coefficients** – these coefficients predict the PI as a function of asset age, describing the curve shown in the graph at the bottom of the screen. The model coefficients should be copied to the prioritization tool; and
- **Sample PI Results** – this is a table showing the PI predicted as a function of age and is equivalent to the graph shown to the right of the table.

The graph at the bottom right of the table shows the predicted PI as a function of age, in addition to the cumulative probability of asset failure (probability that the asset, if not

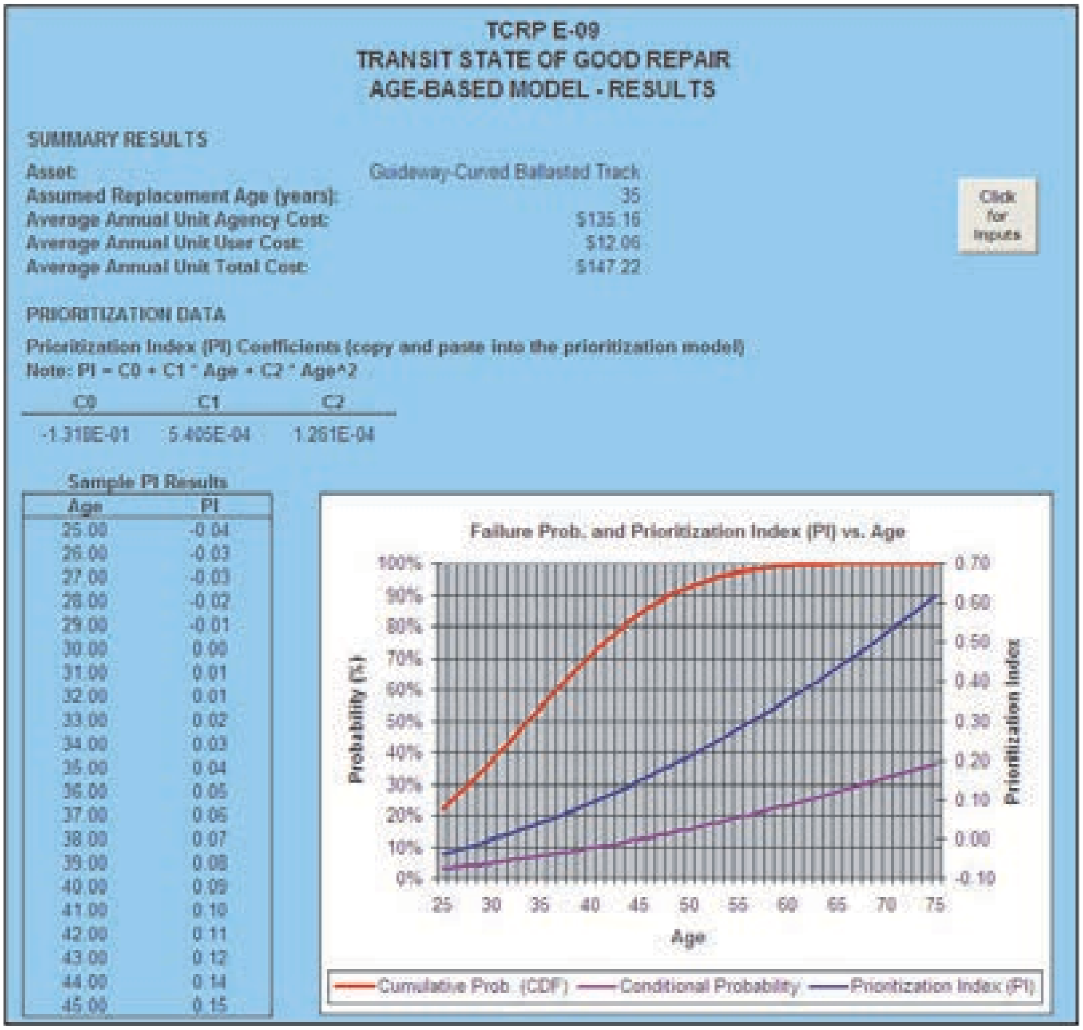


Figure 5-7. Age-based model results.

replaced, would fail by a given age) and the conditional probability of asset failure (probability the asset will fail in the next year, if it has survived to a given age).

5.3.4 Condition-Based Modeling Tool

This tool predicts annual costs and prioritization data for transit assets other than vehicles as a function of asset condition. It is intended for use in analyzing a specific asset type, so a transit agency would likely need to use the tool multiple times to model each of its asset types. To use the tool one must select the asset type and specify a set of parameters for the asset. Figure 5-8 shows the input page for the tool. Required inputs include:

- **Asset Type** – select an asset type from the list, which includes guideway, facility, system and station assets;
- **Unit Agency Replacement Cost** – asset replacement cost specified in the transit agency's preferred units of measure for the asset. For instance, facilities or systems would typically be characterized according to cost per asset, while guideway-related costs may be specified in cost per lineal foot or yard;
- **Unit Agency Rehabilitation Cost** – asset rehabilitation cost specified in the transit agency's preferred units of measure for the asset. If rehabilitation of the asset is considered infeasible, this cost should be set to be greater than or equal to the replacement cost; and
- **Discount Rate** – this parameter quantifies the time value of money and should be set according to transit agency policy or left at its default value if the transit agency has not specified a specific value to use for analysis.

In addition to these parameters one may optionally specify values for an extensive set of parameters shown in the detail page. On this page one can define the condition states for the asset, the actions that can be performed in each state, transit agency and user costs for each asset, and a transition probability matrix that defines the probability of transition from one state

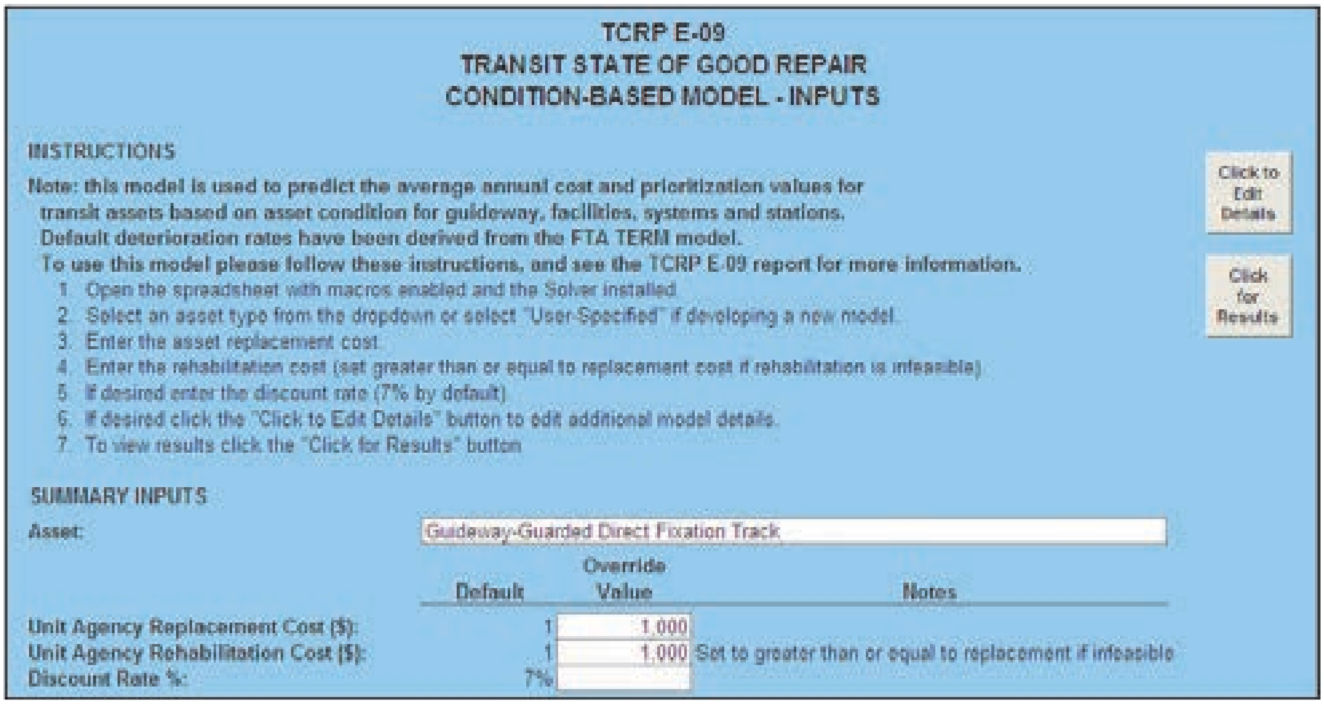


Figure 5-8. Condition-based model inputs.

to another given an action is taken. All of these parameters are populated by default based on what asset is selected in the input page, so one would set these only if developing a new model.

Figure 5-9 shows the results generated by the tool. These include:

- **Average Annual Unit Agency Cost** – average annual unit cost of the vehicle to the transit agency over its life cycle. This includes the replacement cost, maintenance costs, and transit agency failure costs;
- **Average Annual Unit User Cost** – average annual unit cost of the vehicle to transit passengers over the vehicle's life cycle. This includes delay costs from failures and the user replacement cost, if specified;
- **Average Annual Unit Total Cost** – sum of agency and user costs;

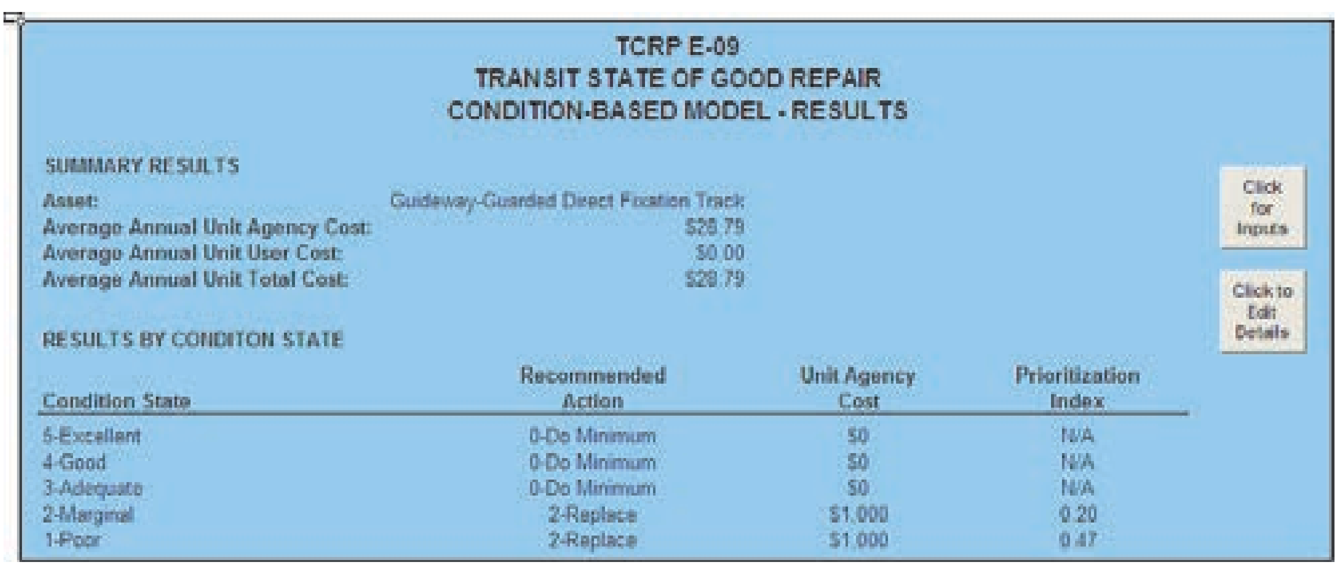


Figure 5-9. Condition-based model results.

- **Recommend Action by Condition State** – action which, if taken in the specified condition, minimizes life cycle costs. Default actions include doing nothing, rehabilitation and replacement;
- **Unit Agency Cost** – unit cost of the recommended action; and
- **PI** – PI value for performing the recommended action in the specified condition.

5.4 Example Analysis

This section describes an example application of the use of the approach and tools described in Section 5.2 and Section 5.3 to follow the process described in Section 4. The example presented here is purely hypothetical and intended solely for illustrative purposes. However, vehicle data provided by the Port Authority of Allegheny County have been used for developing vehicle models that improve the realism of the example analysis.

In the example, rehabilitation and replacement needs are analyzed for the fictitious agency XYZ Transit. The analysis considers rehabilitation and replacement needs for the existing assets of: buses, light rail vehicles, track, and escalators.

XYZ Transit is interested in developing a plan for rehabilitation and replacement of these assets based on needs anticipated in 2013 and 2014. It is assumed that XYZ Transit has previously developed a program for collecting data on existing assets and reporting performance, and has processes in place for performing planned work. Thus, the example focuses on steps 2 to 6 of the framework described in Section 4. The following subsections describe each of these steps.

5.4.1 Analyze Asset Conditions and Performance

Table 5-1 lists the performance measures XYZ Transit uses to characterize the conditions of its existing assets. In the table, two types of measures are used for each of the four asset types included in the analysis: 1) measures used for analysis and 2) summary versions of these measures used for reporting. For instance, when analyzing its needs for buses, XYZ Transit considers a range of user and transit agency costs, as well as the overall percentage of vehicles in the fleet with low emissions. The cost measures are summarized by reporting on the percentage of vehicles in poor condition (requiring replacement) and hours of delay due to road calls.

Table 5-1. XYZ Transit performance measures for existing capital assets.

Asset Type	Performance Measure Used for Detailed Analysis	Summary Measures
Buses	Agency cost (for maintenance, rehabilitation and fuel) User cost (for delay from road calls) Percent of vehicles with low emissions	Percent of vehicles in poor condition (due for replacement) Hours of delay (due to road calls) Percent of vehicles with low emissions
Light Rail Vehicles	Agency cost (for maintenance and rehabilitation) User cost (for delay from failures)	Percent of vehicles in poor condition (due for overhaul or replacement) Hours of delay (due to failures)
Track	Agency cost (for track maintenance planned replacement, and emergency replacement) User cost (for emergency replacement)	Hours of delay (due to slow orders)
Escalators	Agency cost (for refurbishment, replacement and emergency repairs) User cost (for delay due to out-of service escalators) Percent of escalators with safety enhancement	Average availability (percent of time in service) Percent of escalators with safety enhancement

Buses

XYZ Transit's bus fleet is assumed to be similar to that of the Port Authority of Allegheny County. The fleet consists of 14 subfleets together totaling 876 forty-foot buses. Figure 5-4 lists the subfleet numbers, number of vehicles, and accumulated mileage for each subfleet, as well as the parameters used for modeling the bus fleet. The vehicle modeling tool, used with the parameters outlined above, predicts transit agency and user costs and shows benefits of bus replacement. Based on the tool, the cost-minimizing replacement mileage is 530,920 miles (approximately 15 years). The first subfleet recommended for replacement using this model is subfleet 3. Ideally this subfleet would be replaced in 2012 or 2013—the net benefit of replacement relative to deferral shifts from being negative to positive at this point.

An important issue for XYZ Transit is to upgrade its bus fleet to a low emissions fleet as it replaces its buses. Buses purchased in recent years (22.3% of the fleet) are low emissions, but the older buses run on diesel fuel. An additional benefit is considered for replacing a diesel bus with a low emissions bus, and the potential increased cost of low emissions fuel (which is highly dependent on energy costs) is not factored into the analysis. This means that all new buses are low emissions vehicles, but that old buses are replaced only when it is cost-effective to replace them.

Light Rail Vehicles

XYZ Transit's light rail fleet is assumed to be similar to that of the Port Authority of Allegheny County. The fleet consists of 82 vehicles of two different types. These are typically run in two-car consists. Subfleet A consists of 54 vehicles. These were originally built between 1985 and 1987, but substantially reconstructed in 2005. Subfleet B consists of 28 vehicles built in 2003.

Data collected on the light rail fleet includes information on in-service failures, which are measured in terms of mean distance between failures (MDBF), and train delay from in-service failures, as well as data on routine and heavy maintenance spending. This information is collected across both subfleets. Figure 5-10 shows recent trends in MDBF and customer delay with data collected each month and the

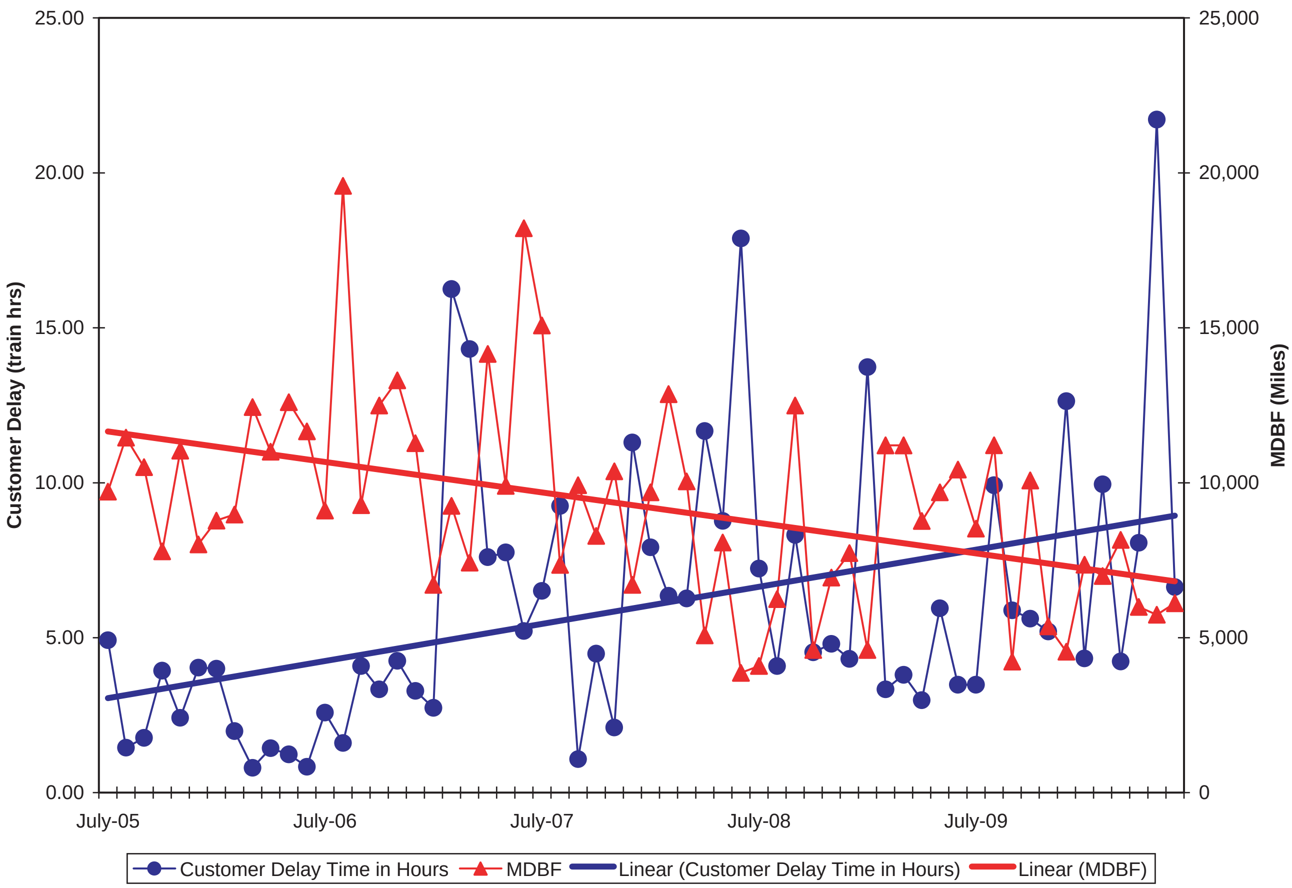


Figure 5-10. XYZ Transit trends in light rail MDBF and delay.

corresponding linear trend line. In the period from 2005 to 2009, MDBF declined from approximately 11,000 to 6,000 miles. Average delay per month increased three to nine train hours. Appendix F details how the information shown in this figure was used to develop a set of model coefficients for using the vehicle modeling tool. As detailed in the appendix, the tool calculates that costs would be minimized if subfleet A is replaced in 2025 at an age of 20 years, and if subfleet B is replaced in 2026 at an age of 23 years. For the sake of illustration, it is assumed that subfleet A is 24 years old in 2012 and thus overdue for replacement.

Table 5-2. XYZ Transit light rail track conditions.

Age (years)	Percent of Network	PI
1-4	20	-0.18
5-9	20	-0.13
10-14	20	-0.07
15-19	20	0.00
20	12	0.04
21	0	0.06
22	4	0.07
23	0	0.09
24	4	0.11
25	0	0.13

Track

XYZ Transit has 25 miles of double-tracked light rail guideway, or 50 miles of track. The track is inspected regularly for defects and traffic is placed under a slow order if a defect is found. Slow orders are placed on 2% of the system each year, though the total amount under slow orders at any one time is much lower than this, as slow orders are addressed as quickly as possible. Routine maintenance costs $5 per lineal foot of track per year, and track replacement costs approximately $100 per lineal foot. If a section of track suffers a defect, it is placed under slow order until it can be repaired. Spot replacements typically involve replacing 100 feet of track. A track failure is estimated to cost $500 per foot, or $50,000 for a 100-foot section. Of this cost, approximately half is an agency cost and half is the user cost of delay resulting from the slow order.

A recent research study performed by ABC University concluded that for XYZ Transit's track, the probability of a track defect severe enough to require immediate repairs can best be predicted as a function of age in years using a Weibull model with a shape parameter of three and a scale parameter of 30. (This is an average value—in practice the deterioration rate varies based on degree of curvature, operating conditions and other factors.) Based on this data, one can determine using the age-based modeling tool that the annualized cost of maintaining track is minimized when track is replaced on approximately a 20-year cycle. In this case, the average annual cost is approximately $1,800 per 100-foot section. Table 5-2 shows the current distribution of track by age and results generated using the tool. The table shows by age of track, the percentage of the system at the corresponding age and the PI for replacement.

Escalators

The fourth asset type included in the analysis (as an example of a condition-based asset) is escalators. XYZ Transit has 40 escalators in its inventory. These are located in above ground and underground light rail and intermodal stations. The agency uses the five-point TERM condition scale for inspecting its escalators on an annual basis, with a five indicating the best condition and one indicating the worst condition. Of the 40 escalators, two are in State 1, two are in State 2, and the remaining escalators are distributed between States 3, 4, and 5.

Appendix F describes the development of a condition-based model for escalators. Based on the inputs specified, the optimal policy for an escalator is to rehabilitate the escalator at a cost of $629,000 if it is in State 1 or State 2, but otherwise do the minimum set of actions. Rehabilitating an escalator in State 1 has a PI of 0.19, while rehabilitating in State 2 has a PI of 0.03.

5.4.2 Generate Rehabilitation and Replacement Alternatives

Once the rehabilitation and replacement policy has been specified, generating rehabilitation/replacement alternatives is a matter of identifying what assets require action based on the policy. Integrating the models described previously, XYZ Transit's policy for the four asset types may be summarized as follows:

- Buses should be replaced at approximately 15 years of age and should be replaced with low emissions buses.
- Light rail vehicles should be overhauled or replaced at 20 to 23 years of age.
- Track should be replaced at approximately 20 years of age.
- Escalators should be refurbished if they are in marginal (State 2) or poor (State 1) condition.

Table 5-3 lists alternatives for the four asset types for 2013 and 2014 based on the policy articulated above. For each alternative the table lists the year for the alternative, the transit agency cost of the alternative, the PI, and additional notes on the impact of the alternative in terms of agency performance. Note that in some cases the alternative has different benefits in the two different years, as the relative benefit of performing needed work tends to increase as the asset's condition worsens. The alternatives shown for one asset in two different years are

Table 5-3. XYZ Transit rehabilitation and replacement alternatives.

Year	Cost ($ 000)	PI	Impact
Replace Bus Subfleet 3 (117 buses)			
2013	46,449	0.01	Increases number of low emissions vehicles, reduces buses in poor condition, reduces delay
2014	46,449	0.02	
Replace Light Rail Vehicle Fleet A (54 vehicles)			
2013	189,000	0.08	Reduces vehicles in poor condition, reduces delay
2014	189,000	0.11	
Replace 20-Year Old Track (4% of system)			
2013	316,800	0.04	Reduces delay
2014	316,800	0.06	
Replace 22-Year Old Track (4% of system)			
2013	105,600	0.07	Reduces delay
2014	105,600	0.09	
Replace 24-Year Old Track (4% of system)			
2013	105,600	0.11	Reduces delay
2014	105,600	0.13	
Rehabilitate Escalators in State 2 (2 escalators)			
2013	1,258	0.03	Increases availability, escalators with enhanced safety
2014	1,258	0.03	
Rehabilitate Escalators in State 1 (2 escalators)			
2013	1,258	0.19	Increases availability, escalators with enhanced safety
2014	1,258	0.19	

mutually exclusive, although in practice most of the projects can be subdivided between years.

5.4.3 Define Scenarios

The next step is to define scenarios for analysis and characterize the results for each scenario. Three scenarios are defined for analysis. Scenario 1 is a "do minimum" scenario where no investments are made. Scenario 2 involves continuing current funding levels for each investment category, with total spending capped at $86 million per year. Historically, funding levels by category have averaged:

- Bus – $20 million per year;
- Rail – $25 million per year;
- Track – $40 million per year; and
- Escalators – $1 million per year.

Scenario 3 completes all recommended work necessary to achieve a state of good repair. Here achieving a state of good repair means that transit agency is following its rehabilitation and replacement policy to help minimize life cycle transit agency and user costs, which is different from maintaining all assets in a "like new" condition.

For this step, the analysis is performed within categories (subject to revision once projects have been prioritized). Table 5-4 summarizes the results by scenario. The table lists, for each of the investment types, the summary measures recommended, the estimated existing value for the measure, and the predicted results for each scenario at the end of the two-year analysis period, computed using data from the analysis tools. In applying the tools, an asset was assumed to be in poor condition if it was in need of replacement or rehabilitation based on the policy.

Based on the results presented in the table, it is clear that Scenario 1 would result in a marked worsening of performance. With this scenario, bus delay would increase by 15%, rail

Table 5-4. XYZ Transit scenario comparison.

Type	Measure	Existing	Scenario		
			1-Minimum (no projects)	2-Current Funding	3-Achieve SGR
Bus	% in poor condition	0	14	7	0
	Hours of delay	110,000	126,000	113,000	111,000
	% with low emissions	22	22	34	36
Rail	% in poor condition	0	66	49	0
	Hours of delay	70	88	76	41
Track	Hours of delay	30,500	38,900	35,400	21,300
Escalators	Average % available	98	97	98	99
	% with improved safety features	10	10	15	20

vehicle delay would increase by 26%, and track delay would increase by 28%. Also, escalator availability would decline and the percentage of vehicles in poor condition would increase dramatically. By contrast, Scenario 3 would keep bus delay constant, and reduce rail vehicle and track delay. Also in this scenario, escalator availability would improve and the percentage of assets with low emissions (for buses) and improved safety features (for escalators) would increase. Scenario 2 would yield results between these extremes. With this scenario, the percentage of vehicles in poor condition and various forms of delay would increase, but not to the same degree as in Scenario 1.

If XYZ Transit were to finalize its future plan based on one of the scenarios, the analysis results could be used to guide development of the investment plan. The preferable outcome would be to achieve a state of good repair, as envisioned in Scenario 3. However, in this example, it is assumed that results of the scenario analysis demonstrated to XYZ Transit management the need for increased funding and the agency was only able to secure an additional $14 million of investment funds for rehabilitation and replacement of existing capital assets, bringing the available funds to $100 million per year. Thus, further analysis is required to determine how best to allocate these funds.

5.4.4 Prioritize Projects

The next step in applying the framework is to prioritize individual projects. In this example, XYZ Transit's calculation of project utility is based strictly upon the economic benefits presented. Table 5-5 shows the results of this calculation. The projects listed are the same as those shown in Table 5-3, but are sorted by PI and ranked. Based on the results in the table, the highest-ranked project is to rehabilitate the escalators in State 1, followed by replacing the 24-year old track. Replacing Light Rail Vehicle Fleet A (assumed to be 24 years old for the sake of this example) is the third-highest project, followed by other track replacement projects, rehabilitating escalators in State 2, and replacing Bus Subfleet 3.

Table 5-5. XYZ Transit project priority calculation.

Project	Cost ($ 000)	PI	Rank
Rehabilitate Escalators in State 1 (2 escalators)	1,258	0.19	1
Replace 24-Year Old Track	105,600	0.11	2
Replace Light Rail Vehicle Fleet A (54 vehicles)	189,000	0.08	3
Replace 22-Year Old Track	105,600	0.07	4
Replace 20-Year Old Track	316,800	0.04	5
Rehabilitate Escalators in State 2 (2 escalators)	1,258	0.03	6
Replace Bus Subfleet 3 (117 buses)	46,449	0.01	7

Appendix F provides an example of the calculation of a utility function incorporating additional benefits for low emissions vehicles and safety benefits not calculated in the analysis, as well accounting for perceptions of agency managers and stakeholders concerning the importance of different types of investments.

5.4.5 Develop the Investment Plan

The final analysis step (before executing the planned work) is to develop the investment plan. In this case, this task consists of determining what projects to perform from the set listed in Table 5-5. The prioritization tool provides a set of recommendations for the plan based strictly upon the budget and PI results. Table 5-6 shows the recommendations generated by the tool, including the initial PI and rank from Table 5-5, the year the work is simulated as being programmed, and the PI in the program year.

Generally speaking, the prioritization tool recommends programming projects in rank order. However, because PI tends to increase from one year to the next, it is possible that a

Table 5-6. Prioritization tool investment plan recommendations.

Project	Initial PI	Initial Rank	Year Prog.	PI in Year Prog.
Rehabilitate Escalators in State 1 (2 escalators)	0.19	1	2013	0.19
Replace 24-Year Old Track	0.11	2	2015	0.15
Replace Light Rail Vehicle Fleet A (54 vehicles)	0.08	3	2014	0.14
Replace 22-Year Old Track	0.07	4	2017	0.17
Replace 20-Year Old Track	0.04	5	2020	0.17
Rehabilitate Escalators in State 2 (2 escalators)	0.03	6	2020	0.03
Replace Bus Subfleet 3 (117 buses)	0.01	7	2020	0.13

project ranked lower initially is programmed before a higher-ranked project because its PI grows faster. This is the case for replacement of Light Rail Vehicle Fleet A. Though ranked third, it is programmed second as its PI increases at a faster rate than the second-ranked project, track replacement.

While the information in the table provides a number of insights, it also hints at the difficultly XYZ Transit has in trying to develop its plan. Put simply, rehabilitation and replacement needs dwarf the available budget of $100 million and defy a straightforward approach to allocation of funds based simply on PI. In practice, projects greater than the available budget may need to be rescoped to address a smaller set of assets, while small projects may need to be combined. Also, it may be necessary to apply constraints on maximum and minimum spending by category or mode to achieve a more balanced solution. However, though such steps may be needed, the prioritization tool nonetheless provides a set of priorities and initial recommendations for XYZ Transit to use for finalizing its plan.

SECTION 6

Conclusions

This research described in this report provides a review of literature related to evaluation of transit capital asset rehabilitation and replacement. It also provides a summary of example transit asset management practices drawn from a set of agency interviews. In addition, the research describes the impacts of investments in asset rehabilitation and presents a framework for evaluating and prioritizing these investments. The analytical approach underlying the framework is detailed, along with a set of spreadsheet tools for supporting the approach.

Transit agencies can use the research results to support the evaluation and prioritization of capital asset rehabilitation and replacement. In particular, the model for analyzing buses can be used with readily available NTD data to predict costs of bus replacement, maintenance, rehabilitation, and fuel, as well as customer delay based on a transit agency's bus replacement strategy. Basic tools and approaches are provided that can be applied to other assets (i.e., rail vehicles, assets for which deterioration can best be predicted based on age, and assets for which deterioration can best be predicted based on asset condition).

Though the results of the research are intended to be of immediate value for transit agencies, several areas have been identified through this effort where additional research may be merited to support further improvements in assessing and addressing state-of-good-repair concerns. These areas include:

- **Implementation guidance for the framework, analytical approach and tools developed through the research.** Though this report provides basic guidance in implementing the research results, stepping through the implementation steps for one or more agencies would serve to help refine the results of the research, and help illustrate the recommended framework and approach for other agencies to follow.
- **Standards for asset data and condition assessment.** A challenge in evaluating rehabilitation and replacement needs is that different agencies use very different approaches for describing their asset inventories and assessing conditions, particularly for fixed assets. Thus, it is difficult to develop common approaches to evaluating needs, or even common definitions for describing basic concepts, such as what assets should be assessed or what constitutes asset rehabilitation. An FTA effort is currently underway to address this need.
- **Synthesis of models and approaches for track and track-related assets used in passenger and freight rail in the United States and abroad.** One conclusion of the literature review is that extensive work has been performed for predicting performance of track and track-related assets, particularly for freight railroads. Modifications would be needed to apply analytical approaches developed for the rail industry, but it may be of benefit for U.S. transit agencies to have additional information on what models and approaches have been implemented for predicting performance of assets such as track, special track work, ties, fasteners, ballast, and other guideway elements.
- **Research on the relationship between asset condition and user impacts such as delay.** The analytical approach developed through the research demonstrates approaches for predicting user costs, such as the cost of delay. Further, the data from the Port Authority of Allegheny County used for the example vehicle models appears to support the concept that user costs tend to increase with accumulated vehicle mileage. However, additional research is needed to better quantify the relationship between asset condition and user cost, and assess the potential for extending the research described here to other transit assets, such as track and stations.
- **Improved high-level models for relating investment levels to performance.** The research points to a need for moving beyond communicating the importance of addressing state-of-good-repair needs based simply upon calculating the cost of replacing assets older than a given age or below a given condition. Work is needed to improve the high-level models used to analyze transit investments, such as those in TERM, to better predict the transit agency and user impacts

of investment decisions. Also, further research is needed to develop improved measures of sustainability, and relate investment levels to sustainability.

- **Quantification of transit agency prioritization strategies.** The example provided of applying the framework demonstrates that even in a simple case with four asset types it is important to develop a prioritization strategy that weighs the value of different types of investments. Transit agencies regularly must prioritize their investments, but little research has been performed to document how agencies prioritize and what constraints they face in the prioritization process. Also, the prioritization approach described in this report implicitly assumes that assets are replaced in-kind, when in fact there may be additional environmental or technological benefits of new assets that should be considered in prioritization. Additional research is needed to quantify this information.
- **Guidance on applying asset management concepts to transit.** The literature review performed for this research yielded a number of guides and manuals concerning transportation asset management, but few that considered transit assets. Further work is needed to adapt general transportation asset management concepts to transit. An FTA effort is currently underway to address this need.

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Acronyms and Abbreviations

AAAPUL	Average Age of Assets as a Percentage of their Useful Life
AAR	Association of American Railroads
AASHTO	American Association of State Highway and Transportation Officials
BART	San Francisco Bay Area Transit District
BCR	benefit cost ratio
BMS	Bridge Management System
BSI	British Standards Institution
CIP	Capital Improvement Program
CO_2	carbon dioxide
COTS	commercial off the shelf
CTA	Chicago Transit Authority
DOT	department of transportation
DRPT	Department of Rail & Public Transit
FHWA	Federal Highway Administration
FRA	Federal Rail Administration
FTA	Federal Transit Administration
FTE	full time equivalent
HERS	Highway Economic Requirements System
IIMM	International Infrastructure Management Manual
ISTEA	Intermodal Surface Transportation Efficiency Act
LCH	lost customer hours
LIDAR	light detection and ranging
LU	London Underground
MAU	multi-attribute utility
MBTA	Massachusetts Bay Transportation Authority
MDBF	mean distance between failures
MTA	Metropolitan Transit Authority
MTBF	mean time between failures
MTC	Metropolitan Transportation Commission
MTRCL	Mass Transit Railway Corporation Limited
MPO	metropolitan planning organization
MUNI	San Francisco Municipal Railway
NAMS Group	National Asset Management Steering Group
NBIAS	National Bridge Investment Analysis System
NCHRP	National Cooperative Highway Research Program
NJDOT	New Jersey Department of Transportation
NJ Transit	New Jersey Transit

NPV	net present value
NTD	National Transit Database
NTSB	National Transportation Safety Board
NYCT	New York City Transit
OEM	original equipment manufacturer
O&M	operation and maintenance
OPM	Ordered Probit Model
PAS 55	Publicly Available Specification 55
PI	prioritization index
PIARC	World Road Association
PROGGRES	Program Guidance and Grant Evaluation System
PTMS	Public Transportation Management Systems
RAMS	Reliability, Availability, Maintainability, and Safety
RSL	remaining service life
RTA	Cleveland Regional Transit Authority
RTCI	Regional Transit Capital Inventory
RTP	regional transportation plan
SGR	state of good repair
SEMCOG	Southeast Michigan Council of Governments
SEPTA	Southeastern Pennsylvania Transportation Authority
TAMP	Transit Asset Management Program
TCRP	Transit Cooperative Research Program
TERM	Transit Economic Requirements Model
TLM	track laying machine
TTC	Toronto Transit Commission
WSDOT	Washington State Department of Transportation

APPENDIX A

Review Approach Details

This appendix provides additional detail on the review summarized in Section 2. Section A.1 provides detail on the approach to the literature review and interviews. Section A.2 summarizes related research efforts, and Section A.3 lists case studies included in the review.

A.1 Review Approach

To perform the review the research team first searched the following databases for relevant literature:

- Transportation Research Board (TRB) Transportation Research Information Services (TRIS);
- TRB Research in Progress (RiP) database;
- Transportation Libraries Catalog (TLCat);
- U.S. Department of Commerce National Technical Information Service (NTIS) database;
- Research and Innovative Technology Administration (RITA) National Transportation Library (NTL); and
- WorldCat.

Resources gained from the initial search were supplemented by performing web searches on common search engines, including Google, Bing, and Yahoo. When accessing the reference databases and search engines listed above, the research team used keywords including: transit management; transit state of good repair; investment prioritization; asset management; infrastructure management; performance metrics and measurement; and program and project management.

The initial literature search was supplemented by accessing online publications and/or consulting directly the following list of target groups and information resources:

- FTA, which has published a number of transit state of good repair reports and presentations, including materials from FTA's State of Good Repair Roundtables;
- Other federal agencies, including the Federal Rail Administration (FRA), Federal Highway Administration (FHWA), U.S. Department of Transportation (U.S. DOT), and Government Accountability Office (GAO);
- Transit agencies;
- State DOT and other state agencies;
- University Transportation Centers of Excellence and their publications and graduate dissertations related to asset management;
- TRB publications, including the Transportation Research Record, Transportation Research Circulars, and reports and syntheses prepared for TCRP, the National Highway Cooperative Research Program (NCHRP), Aviation Cooperative Research Program (ACRP), National Cooperative Freight Research Program (NCFRP) and Strategic Highway Research Program (SHRP); and
- Materials related to transit asset management and state of good repair from TCRP's June 2010 International Studies Mission on Sustainable Public Transportation Funding – Innovative Planning and Financing Strategies.

Appendix B provides an annotated bibliography of the materials reviewed. Note that a number of the references included their own reviews of relevant literature. These cases are indicated in Section 2. The research team relied on these reviews to help summarize the state of the practice, particularly in industries outside of transit, and to identify additional resources to include in the review.

A set of targeted interviews of transit agencies and other organizations were performed to supplement the literature review. The research team worked with the research panel to identify a candidate set of organizations to interview based on the following criteria:

- The organizations identified should include transit organizations of different sizes and in different regions of the United States.
- At least two of the transit agencies identified should be small- or mid-sized agencies focused on buses, and least two should be large agencies with a mix of bus and fixed guideway operations.
- At least one Class 1 railroad should be included in the set of organizations.

- At least one transit agency outside the United States should be identified.
- At least two metropolitan or state-level agencies that assist in prioritizing transit investments between multiple agencies should be identified.
- At least two state DOTs should be identified illustrating best practices in prioritizing pavement and bridge rehabilitation and replacement.
- Other types of transportation organizations (e.g., ports and airports) may be identified, to the extent that the review yields best practice examples.
- Each organization identified should exhibit best practices in some aspect of asset rehabilitation and replacement prioritization.
- For each organization identified, there must either be sufficient information collected through the review to support evaluation, or there should be an organization contact willing to provide additional information through a telephone interview to support the research.

Following finalization of the set of candidate interviewees, the research team contacted each organization to determine its willingness to participate in the interview process and schedule a time for an interview. The interview guide included in Appendix C was used to structure the interviews and sent to each interviewee in advance. All interviews were performed via telephone, with additional questions and requests for information handled through telephone or email. Table A-1 lists the organizations interviewed, with the name of the primary contact at each organization, interview date and focus area of each interview.

The interviews yielded additional materials that were incorporated in the review, information on existing practices at the organizations interviewed, and general information on existing and best practices related to prioritization of transit asset management and rehabilitation and replacement of transit assets. To the extent that the interviews yielded additional reports, presentations, manuals or other written materials, these were incorporated in the review and are summarized in Section 2. Notable existing practices identified through the interviews are described in Appendix D.

A.2 Related Research Efforts

A number of research efforts are currently underway that are related to transit state of good repair. Their results may provide useful insights and advancements pertinent

Table A-1. Organizations identified for existing practice interviews.

Organization	Location	Primary Contact	Job Title/ Responsibility	Interview Date	Focus Area(s)
National Railroad Passenger Corporation (Amtrak)	Washington, D.C.	David Staplin	Deputy Chief Engineer of Track	January 31, 2011	Track infrastructure condition assessment (see Appendix D)
Austin Capital Metropolitan Transportation Authority (Capital Metro)	Austin, TX	Carl Woodby	Director of Maintenance	February 8, 2011	Bus maintenance and replacement
Chapel Hill Transit	Chapel Hill, NC	Carl Rokos	Maintenance Superintendent	January 27, 2011	Bus maintenance and replacement
London Underground (LU)	London, England	Kevin Dunning	Head of Maintenance Development	February 8, 2011	Performance reporting (see Appendix D)
Long Beach Transit (LBT)	Long Beach, CA	Rolando Cruz	Executive Director and VP of Maintenance and Facilities	January 11, 2011	Bus maintenance and replacement
Massachusetts Bay Transportation Authority (MBTA)	Boston, MA	Jeff Gonneville	Chief Mechanical Officer	February 10, 2011	State of Good Repair Database, project prioritization (see Appendix D)
Metropolitan Atlanta Rapid Transit Authority (MARTA)	Atlanta, GA	David Springstead	Senior Director of Engineering and Development	February 7, 2011	Integrated maintenance management (See Appendix D)

Table A-1. (Continued).

Organization	Location	Primary Contact	Job Title/ Responsibility	Interview Date	Focus Area(s)
Metropolitan Transportation Commission (Bay Area) (MTC)	Oakland, CA	Glen Tepke	Transit Capital Priorities Manager	January 28, 2011	Regional Transit Capital Inventory, project prioritization (see Appendix D)
New Jersey Department of Transportation (NJDOT)	Trenton, NJ	Robert Harris	Project Manager	January 14, 2011	Capital investment strategy (see Appendix D)
Metropolitan Transportation Authority (MTA) New York City Transit (NYCT)	New York City, NY	John Decker	Director of Capital Planning and Budget	February 7, 2011	Performance reporting (see Appendix D)
Washington State Department of Transportation (WSDOT)	Olympia, WA	Faris Al-Memar	Systems Analysis and Planning Manager	January 12, 2011	Performance reporting (see Appendix D)

to characterizing the impacts of investments in rehabilitation and replacement of transit assets. However, they were still underway and/or pending publication at the time of this review. Table A-2 lists each effort, providing the title, sponsoring agency, and expected completion date based on data from the TRB RiP database. Of these, TCRP Synthesis *J-07 Transit Asset Condition Reporting,* is of particular relevance, as it reviews approaches to reporting condition for transit state-of-good-repair analysis. Also relevant is the set of six asset management pilot projects initiated by FTA in 2011. These projects are intended to demonstrate solutions to transit state-of-good-repair challenges, and will likely result in further advancements in this area of research.

Table A-2. Overview of active related research efforts.

Title	Sponsor	Expected Completion
Comprehensive Transportation Asset Management: Risk-Based Inventory Expansion and Data Needs	Georgia Department of Transportation	2011
Developing a Framework for the Prioritization of Infrastructure Improvements	Pennsylvania Transportation Institute	2011
Transit Bus Fleet Management and Optimization Models Addressing New Engine Technologies and Emissions Constraints	King County Metro	2011
TCRP Synthesis J-07/Topic SG-11: Transit Asset Condition Reporting	TRB	2011
NCHRP Project 14-21: Resource Allocation Framework to Meet Highway Asset Preservation Needs	TRB	2012
NCHRP Project 14-24: Convincing the Stakeholders: Developing a Guide for Communicating Maintenance and Preservation Needs	TRB	2012
NCHRP Project 14-20: Consequences of Delayed Maintenance	TRB	2013
TCRP Synthesis J-07/Topic SE-06: Successful Maintenance and Safety Practices for Elevators and Escalators in U.S. Transit Agencies	TRB	not specified
Development of Transit Asset Management Guidelines and Training	FTA	not specified
Asset Condition Assessment Research	FTA	not specified
Asset Management Pilot Projects	FTA	not specified

A.3 Case Studies

Table A-3 summarizes the relevant case studies identified through the review. The case studies are organized by organization type and specific organization. Also, Table A-3 provides a brief summary of the best practice area described in the literature, and a reference for further information, noting cases where multiple facets of an organization's practices related to this research are described. Appendix D provides more detailed case studies for eleven practices at eight agencies identified through the interview process.

Table A-3. Case studies included in the review.

Type	Organization	Description	Source
U.S. Transit Agencies	Bi-State Development Agency (St. Louis Metro)	State of Good Repair Program	(*1, 2*)
	Capital Metro	State of Good Repair Program	Project Interview
	Chapel Hill Transit	State of Good Repair Program	(*1, 3*)
	Chicago Transit Authority (CTA)	State of Good Repair Program	(*1, 4, 5*)
	Dallas Area Rapid Transit (DART)	Asset Inventory and Condition	(*6*)
	Foothills Transit	Bus Maintenance Audits	(*7*)
	Greater Richmond Transit Commission (GRTC)	State of Good Repair Program	(*1*)
	King County Metro Transit	State of Good Repair Program	(*8*)
	Long Beach Transit (LBT)	Maintenance Policies & Procedures	Appendix D
	Metropolitan Atlanta Rapid Transit Authority (MARTA)	Integrated Maintenance Management	Appendix D (*1, 9, 10*)
	Massachusetts Bay Transportation Authority (MBTA)	State of Good Repair Database	Appendix D, (*11-15*)
		Project Prioritization	Appendix D
	Metropolitan Transportation Authority (MTA) New York City Transit (NYCT)	State of Good Repair Program	Appendix D (*16-19*)
		Performance Reporting	Appendix D
	New Jersey Transit (NJT)	State of Good Repair Program	(*20*)
	Niagara Frontier Transportation Authority (NFTA)	State of Good Repair Program	(*21*)
	Washington Metropolitan Area Transit Authority (WMATA)	State of Good Repair Program	(*22*)
Other U.S. Transit-Related	Metropolitan Transportation Commission (MTC)	Investment Needs Analysis	Appendix D (*1, 23*)
		Project Prioritization	Appendix D
	Virginia Department of Rail and Public Transit (DRPT)	Investment Needs Analysis	(*1, 24*)

Table A-3. (Continued).

Type	Organization	Description	Source
International Transit Agencies	London Underground (LU)	Performance Reporting	Appendix D
	Hong Kong Mass Transit Railway Corporation Limited (MTRCL)	Performance Reporting	(*25*)
	Toronto Transit Commission (TTC)	State of Good Repair Program	(*1*)
	Victoria Department of Transport (Australia)	State of Good Repair Program	(*1*)
State DOT	Florida Department of Transportation (DOT)	Asset Management Program	(*26*)
	Maryland State Highway Agency	Project Prioritization	(*27*)
	Missouri DOT	Asset Management Program	(*26, 27*)
	New Jersey DOT	Capital Investment Strategy	Appendix D
	North Carolina DOT	Performance Management	(*27*)
	Ohio DOT	Performance Management	(*26*)
	Utah DOT	Asset Management Program	(*27*)
	Virginia DOT	Asset Management Program	(*1*)
	Washington State DOT (WSDOT)	Performance Reporting	Appendix D
	Wisconsin DOT	Asset Management Program	(*26*)
	Wyoming DOT	Project Prioritization	(*26*)
Railroad	Amtrak	Infrastructure Condition Assessment	Appendix D
	United Kingdom Department for Transport	Railroad Risk Management	(*28*)
	U.S. Class I Railroads	Condition-Based Maintenance	(*29, 30*)
Other	Metrowater (Australia)	Asset Management Program	(*31*)
	National Grid Transco (UK)	Asset Management Program	(*31*)
	New Zealand Transport Agency	Asset Management Program	(*26, 31*)
	Province of British Columbia	Performance Management	(*31*)
	Tillamook County, Oregon	Asset Management Program	(*26*)
	Transport Scotland	Asset Management Program	(*26*)
	United Kingdom Water Industry Research	Asset Management Program	(*28*)
	Upper Occoquan Service Authority (Centreville, VA)	Risk Management in Water/Wastewater	(*32*)

A.4 Appendix A References

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APPENDIX B

Annotated Bibliography

B.1 General Asset Management Guidance

Cambridge Systematics, Inc. *NCHRP Report 446: A Guidebook for Performance-Based Transportation Planning.* TRB, National Research Council, Washington, D.C., 2000.

This report provides guidance to improve the development, implementation, and management of multimodal transportation plans and programs. It develops a framework for a performance-based planning process, which includes identifying goals and quantifiable objectives, defining measures that relate to those goals and objectives, identifying the analytical methods and data required to generate the performance measures, and applying the measures in a process of alternatives evaluation, decision support, and ongoing monitoring. The report details a set of 11 case studies describing best practices related to performance-based transportation planning processes used by various national, state, local, and private organizations. Also, it provides a library of performance measures organized by objective, with references for each measure.

Cambridge Systematics, Inc., Parsons Brinckerhoff Quade & Douglas, Inc., Roy Jorgensen Associates, Inc., and Thompson, P.T. *AASHTO Transportation Asset Management Guide.* American Association of State Highway and Transportation Officials (AASHTO), 2002.

This guide is designed to help transportation agencies develop and apply the principles, techniques, and tools that can advance the management of their transportation assets. It describes transportation asset management as a way of doing business to build, preserve, and operate facilities more cost-effectively with improved asset performance, deliver to customers the best value for the public tax dollars spent, and enhance the credibility and accountability of the transportation agency to its governing executive and legislative bodies. The guide defines principles consistent with an asset management approach, and provides a self-assessment for agencies to use to evaluate the degree to which their agency has implemented best practices in asset management. The guide includes a number of best practice examples that illustrate the application of asset management concepts.

Cambridge Systematics, Inc., PB Consult, and System Metrics Group, Inc. *NCHRP Report 545: Analytical Tools for Asset Management.* Transportation Research Board of the National Academies, Washington, D.C., 2005.

This report reviews needs for analytical tools to support transportation asset management and reviews existing tools including: management systems; tools for evaluating investment levels and trade-offs; tools for identifying needs and solutions; tools for evaluating options and tools for monitoring results. The report presents a gap assessment that compares the existing tools to the tools needed, and describes the development of two analytical tools intended to address the gaps: AssetManager NT and PT. AssetManager NT is a tool for evaluating network-level trade-offs in funding between different asset/investment categories. AssetManager PT is a program-level tool for comparing different projects.

Cambridge Systematics, Inc., PB Consult, and Texas Transportation Institute. *NCHRP Report 551: Performance Measures and Targets for Transportation Asset Management.* Transportation Research Board of the National Academies, Washington, D.C., 2006.

This report provides a comprehensive review of the use of performance measures for transportation asset management, focusing primarily on highway asset management. The report is divided into two volumes. Volume I is a research report that reviews current practices in use of performance measures for asset management, recommends criteria for selecting performance measures, discusses considerations in designing and using performance measures, and presents a framework for using performance measures to support asset management. Volume II is a practical guide for identifying performance measures and setting performance targets. It presents a step-by-step approach for agencies to follow, encompassing identification of measures, integration of performance measures into an organization, and establishing performance targets.

National Asset Management Steering Group (NAMS). *International Infrastructure Management Manual (IIMM).* Association of Local Government Engineering NZ Inc (INGENIUM) and the Institute of Public Works Engineering of Australia (IPWEA), 2006.

This manual details principles, processes and examples of infrastructure asset management. It introduces asset management concepts and describes how to implement an asset management approach, including enabling processes for asset management and supporting systems and data. The enabling processes discussed in the manual include levels of services, demand forecasting, condition assessment, optimized decision-making (including optimizing resource allocation), maintenance management, and financial planning. Also, the manual includes country-specific guidance for Australia, New Zealand, South Africa, the United Kingdom, and the United States. The manual can be used for managing any infrastructure asset. Nonetheless, much of the guidance and many of the examples pertain to managing transportation assets. The manual is notable for its broad scope, and extensive set of examples and case studies.

British Standards Institution (BSI). *Publicly Available Specification (PAS) 55.* British Standards Institution, 2008.

PAS 55 is a specification from the BSI and the International Asset Management Committee designed to provide guidance in managing physical assets. The standard includes two parts. PAS 55-1 is a standard for "optimized management of physical assets." PAS 55-2 is a set of guidelines for implementation. PAS 55 defines asset management as "the systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational strategic plan." The asset management concepts detailed in PAS 55 are conceptually similar to those in the *AASHTO Transportation Asset Management Guide* and supplement, and in the IIMM. Like the IIMM, PAS 55 is intended to apply to a range of infrastructure assets, including, but not limited to, transportation assets. PAS 55 includes a 28-point requirements checklist describing mechanisms for establishing whole life cycle planning, risk management, and cost/benefit analyses within the day-to-day activities of capital project implementation. Requirements include identifying and considering the needs of stakeholders over the life cycle of the asset, specifying the interventions needed for minimum costs, and optimizing the timing of work to create the right groups of projects.

Hooper, R., Armitage, R., Gallagher, K.A., and Osorio, T. *Whole-Life Infrastructure Asset Management: Good Practice Guide for Civil Infrastructure.* CIRIA, 2009.

This guide discusses the strategic and tactical aspects of managing long-life civil engineering infrastructure assets. The guide is meant to be used in conjunction with British Standards Institution's *Publicly Available Specification (PAS) 55* and National Asset Management Steering Group's *International Infrastructure Management Manual.* It provides the principles, best practices, and case studies for setting asset management policy and strategy, determining asset performance measures and targets, and developing and carrying out asset management plans. It includes guidance on contractual agreements; identifying, assessing, and controlling risks; meeting regulations and requirements placed through voluntary agreements; and training and information control. It recommends comparing current performance with targets to prioritize asset investments. The case studies on various civil infrastructure owners in the UK provide detailed examples of effectively approaching and implementing asset management.

AECOM, Thompson, P.D. and Spy Pond Partners. *AASHTO Transportation Asset Management Guide: A Focus on Implementation.* AASHTO, 2011.

This guide is a supplement to AASHTO's 2002 *Transportation Asset Management Guide* described above. It provides guidance to transportation agencies on how to implement asset management concepts to achieve the most from financial resources, preserve highway assets, and provide customers with expected service. The guide is organized into three parts. Part I describes strategic considerations in implementing an asset management approach, including the process of setting an agency's direction with respect to asset management, aligning the organization with an asset management approach, and developing a transportation asset management plan (TAMP). Part II details enabling processes, systems and tools for supporting asset management, including service planning, life cycle management, information systems, and data collection. Part III of the guide is a set of appendices with example asset management plans, and a set of in-depth case studies.

B.2 Transit Asset Management and State of Good Repair

Kuiper, W. *Three Case Studies: The Impact of Deferred Maintenance in Rail Transit.* Technical Report UMTA-IT-06-0242-85-1 prepared for UMTA. UMTA, 1985.

This report describes how deferred maintenance can deteriorate transit system performance and increase costs through three case studies. The first study discusses performance trends for the period between 1974 and 1984 for New York City Transit Authority's (NYCT) R-36 fleet. At the start of the period, the fleet performed reliably, as reflected by the large Average Miles Between Delays (AMBD). A budget crisis in the late 1970s led to fewer maintenance staff, inspections, and parts, and by 1984, the AMBD and quality of service declined significantly. The second study discusses the major attention needed by NYCT's tracks and switches in 1983 because of the lack of replacement work in the 1970s and early 1980s. Since substandard tracks required more maintenance than tracks in good condition, repair requirements increased. The third study involves San Francisco MUNI's Light Rail Vehicle (LRV) fleet and its changes in reliability. MUNI was initially ill prepared to maintain the LRV fleet, which failed frequently. By increasing its emphasis on the preventive maintenance program and modifying the door and brake systems, MUNI realized a significant improvement in its LRV fleet performance.

Parsons Brinckerhoff Quade & Douglas. *TCRP Report 5: Guidelines for Development of Public Transportation Facilities and Equipment Management Systems.* TRB, National Research Council, Washington, D.C., 1995.

This report provides an overview of a Public Transportation Facilities and Equipment Management System (PTMS) and provides implementation guidance to state, MPO, transit, and other agencies. PTMS is a systematic process that collects and analyzes information on the condition and cost of transit assets on a continual basis. The report reviews the development process and component characteristics of a PTMS database, which structures and includes information required to identify an asset and its current condition and function; describe and quantify potential actions that can be taken to address deficiencies; prioritize the needed actions; and evaluate the alternatives. It also provides guidance on collecting data on assets, developing the means to determine the condition of those assets and their useful life, and developing the strategies to maintain and replace those assets.

Kittleson &Associates, Urbitran, LKC Consulting, MORPACE International, Queensland University of Technology, and Nakanishi, Y. *TCRP Report 88: Guidelines for Development of Public Transportation Facilities and Equipment Management Systems. TRB, National Research Council, Washington, D.C., 1995.*

This report provides guidance for transit system managers in developing a performance-measurement system that addresses customer and community issues. It presents characteristics of an effective performance measurement system that reflects different points of view and emphasizes customer satisfaction. Twelve case studies provide examples of how transit agencies have successfully used performance measures. To implement a performance-measurement program, it proposes that agencies use an eight-step process: define goals and objectives; generate management support; identify users, stakeholders, and constraints; select performance measures and develop consensus; test and implement the program; monitor and report performance; integrate results into agency decision making; and review and update the program. For each step, the report provides the tasks involved and examples of how transit agencies have accomplished that step.

The report also contains a library of performance measures and categorizes them based on their focus. For each measure, it provides the use, mode, scope, applicable system size, audience, example target values, data requirements, and the factors that influence it. It also discusses data collection sources and techniques, methods to manage the data, methods to set performance standards, and reporting performance.

Yoder, S. and DeLaurentiis, J. "The Framework for a Regional Transit Asset Management System." In *Institute of Transportation Engineers Journal,* Vol. 73, No. 9, pp. 42–47. Institute of Transportation Engineers, 2003.

This paper describes a system for displaying summary asset and project data developed by the Regional Transportation Authority (RTA) in Chicago. The paper details the initial version of the Regional Transit Asset Management System (RTAMS). The system integrates asset and project data from the Chicago Transit Authority (CTA), the Northeast Illinois Regional Commuter Railroad Corporation (METRA) and Pace. The paper describes plans for future versions of RTAMS, which will implement the CTA condition assessment system (similar to that used in TERM) to display current and predicted future asset conditions.

Khasnabis, S., Bartus, J., and Ellis, R. *Optimal Resource Allocation for the Purchase of New Buses and the Rebuilding of Existing Buses as a Part of a Transit Asset Management Strategy for State DOTs.* University of Wisconsin, Madison, 2003.

This report details a set of models for optimal allocation of capital funding for bus fleets. State DOTs can use the first model to allocate dollars between bus replacement, rehabilitation, and remanufacturing programs to maximize the weighted fleet life of all the buses that are being purchased or rebuilt subject to constraints on the budget and total number of buses. The resulting distribution of dollars serves as an input into the second model, which is used for allocating dollars among constituent transit agencies and maximizing the weighted averages of the remaining life of the buses across the agencies. The authors demonstrate the effectiveness of this strategy by testing it on data provided by the Michigan Department of Transportation for medium sized buses over a seven-year period and showing how it would improve the net present worth of the fleet. It is worth noting that this report builds on previous papers published by the authors which appear in *Transportation Research Record 1669* and *1731.*

Keles, P. and Hartman, J. "Case Study: Bus Fleet Replacement." In *The Engineering Economist,* Vol. 49. No. 3, pp. 253–278. Taylor & Francis, 2004.

This paper formulates an approach to determine the optimal replacement schedule for each bus in a transit fleet considering both replacement timing and the selection of suppliers. The authors formulate a parallel replacement problem that considers the impact of: multiple types of assets with varying conditions; multiple suppliers; decision points concerning when to purchase, retain, or salvage the buses; and potential economies of scale. The formulation results in an objective function that minimizes the discounted cash flow (purchase, operations and maintenance costs less salvage values) for the fleet subject to constraints on the budget and availability of assets. The authors use bus data gathered from a number of sources to gain insight on the sensitivity of costs and salvage values, degree of differentiation between suppliers, purchasing scale, and constraints on the total cost.

Khasnabis, S., Bartus, J., and Ellis, R.D. "An Asset Management Strategy for State DOT's to Meet Long-Term Transit Fleet Needs." Presentation at the 83rd Annual Meeting of the Transportation Research Board, 2004.

This paper summarizes the materials detailed in the research report *Optimal Resource Allocation for the Purchase of New Buses and the Rebuilding of Existing Buses as a Part of a Transit Asset Management Strategy for State DOTs* by the same authors described above.

Li, Q., Zhao, H., and XingPing, Y. "Decision-Making Modeling for Rural and Small Urban Transit Asset Management." Presentation at the 83rd Annual Meeting of the Transportation Research Board, 2004.

This paper describes a framework that rural and small urban transit agencies can use to make investment decisions. It develops a probabilistic deterioration model that can be used to predict future conditions of vehicles. The model is an Ordered Probit Model (OPM) that links maintenance spending and vehicle age and mileage to FTA condition ratings. Agencies can use the OPM to calculate the expected opportunity gain (EOG), which is a measure of change in life years for a vehicle. The paper proposes the selection of investments with the highest ratio of EOG to maintenance cost as a method for optimal allocation of funds.

Anderson, M.D. and Davenport, N.S. *A Rural Transit Asset Management System.* Technical Report UTCA No. 04401 prepared for Alabama Department of Transportation. University Transportation Center for Alabama, 2005.

This report documents the creation of a geographic information system (GIS) based asset management system for the Alabama Department of Transportation (ALDOT) to manage transit vehicles. The system enables ALDOT to make vehicle condition predictions, identify vehicles that need to be replaced each year, and determine future funding and budgetary needs. It uses a linear regression model that expresses vehicle condition rating as a function of its age, total miles traveled, annual mileage on unpaved roads, presence of wheel chair lift equipment, and percentage of population that is over 65 years old. The report demonstrates how the model can be used to project the average condition rating for the system as a function of funding by developing three funding scenarios. In each scenario, the vehicles with the lowest condition rating are dropped and replaced with vehicles with an averaged 5-year price.

Centeno, G., Chaudhary, R. and Lopez, P. "Developing Standard Times for Repair Activities for Transit Vehicles." In *Transportation Research Record 1927.* Transportation Research Board of the National Academies, Washington, D.C., 2005.

This paper presents a method to develop standards to determine efficiency, utilization, and productivity of repair activities for transit vehicles, and discusses the results of applying this method to three transit agencies in Central Florida. Steps involved include identifying the critical task, making an adequate number of sample readings, classification of processes involved in the task, and averaging all valid observations to produce standard times for each element. The paper documents how the development of standard times for repairing brakes and preventive maintenance of buses at the agencies in Florida led to minimization of redundant operations, elimination of worker activities not related to the tasks, consistency in maintenance practices, and reduced time to perform tasks.

Transport for London. *Transport for London's 5-Year Investment Programme 2005/06-09/10 for London Underground.* 2005.

This document describes all London Underground projects between 2005 and 2010 that would renew or upgrade assets. It includes the assets managed by London Underground and the Public-Private Partnership contractor. The overall program is organized by asset type, and each asset program is divided into portfolios, which are composed of projects that are jointly managed to provide outcomes. For each portfolio, the document provides the expected benefits, an inventory of the assets that would be impacted, the asset condition benchmarks that are to be used, milestones, and spending breakdown by fiscal year. For projects over £2 million, it provides brief justification and the benefit/cost ratio.

MBTA. *State of Good Repair Report: Key Infrastructure and Capital Spending Issues.* MBTA, 2006.

This report details the MBTA's SGR needs, developed using the SGR database described in subsequent references. The report provides an overview of the MBTA system, documents current conditions in terms of percent of assets exceeding their useful life, and shows predicted asset conditions for four different funding scenarios: unconstrained funding for addressing SGR-related needs, $410M/year, $470M/year, $620M/year. For each scenario the reports show projections generated using the SGR database of the percent of assets predicted to exceed their useful life in 2024 (at the end of the 20-year analysis period) and the projected spending by asset categories. Results are shown for each of 15 asset categories.

Booz Allen Hamilton Inc. *Useful Life of Transit Buses and Vans.* Technical Report FTA VA-26-7229-07.1 prepared for FTA. FTA, 2007.

This report describes research to evaluate the FTA minimum service-life requirements for buses. Transit agencies are required to use buses and vans purchased with federal money for a minimum number of years or miles to ensure adequate outcomes for tax payers' investments (typically 12 years). The research assesses the financial impact of these requirements on transit agencies. The report includes an engineering analysis of the life cycle costs of bus operations. Costs generally increase with higher annual mileage, as well with decreasing operating speeds, which reflect frequent stops and starts. Also the analysis found that vehicles that receive mid-life overhauls have higher life cycle costs than those that are rehabilitated continuously. The report concludes that actual retirement ages, and the cost-effective retirement age, generally exceed the minimums established by FTA.

Scarf, P., Dwight, R., McCusker, A. and Chan, A. "Asset Replacement for an Urban Railway Using a Modified Two-Cycle Replacement Model." In *Journal of the Operational Research Society* Vol. 58, pp. 1123-1137. Operational Research Society, 2007.

This paper reviews approaches for modeling replacement of capital assets, and proposes a modified version of a two-cycle model for use in modeling replacement of escalators for the Mass Transit Railway Corporation Limited (MTRCL) of Hong Kong. The model proposed considers the scenario in which an asset should be replaced periodically over a given time horizon, with the replacement decision made conditional based on the age of the asset. Also, the model considers penalty costs associated with failure of the asset and delay to users in the event of asset failure. The paper shows representative results obtained using the model in terms of the annual cost incurred per escalator and the predicted annual number of delays per escalator.

Van Hampton, T. "*Chicago Rail System on Verge of Collapse.*" In *Engineering News Record,* Vol. 259, No. 19, 2007, pp. 66–67.

This article discusses issues faced by the Chicago Transit Authority (CTA) due to lack of funding for preservation of existing assets. It discusses the deteriorated conditions of the assets, speed restrictions instituted to avoid derailments, the possible need to cut service and jobs, and threats to economic development. The article reports that CTA would require approximately $8.7B in investment to attain a state-of-good repair, but that existing funds are far short of this level.

Cambridge Systematics, and McDonald Transit Associates, Inc. *Capital Metro Peer Review Quadrennial Performance Audit.* Report prepared for the Capital Area Metropolitan Planning Organization. 2008.

This report discusses the performance and statutory compliance of the Capital Metropolitan Transportation Authority (Capital Metro), compares Capital Metro to transit agencies in cities similar to Austin, and provides recommendations for Capital Metro to improve its governance and cost efficiency. It discusses trends according to the following performance indicators: operating cost per passenger, operating cost per revenue hour and per revenue mile, sales and use tax receipts per passenger, fare recovery rate, average vehicle occupancy, on-time performance, number of accidents per 100,000 miles, and number of miles between mechanical road calls. It describes the assessment process used to conclude that Capital Metro complies with Texas state law. It discusses Capital Metro's regional transportation planning, organization, governance, and funding challenges and describes the actions that peer agencies are taking to tackle similar issues. Finally, it provides steps Capital Metro can take to clarify roles in the planning process, improve its financing, and improve its relationship with the workforce.

Davis, J.R. "MBTA State of Good Repair Database." Presented at the FTA CEO Panel of the 2008 Annual Meeting of the American Public Transportation Association, 2008.

The presentation describes the Massachusetts Bay Transportation Authority (MBTA) efforts to develop its SGR database. The MBTA began to focus on SGR activities after a series of realizations regarding the need to prioritize the maintenance of existing assets over system expansion, particularly within the context of "forward funding" which required the MBTA to adopt a yearly constrained budget, as compared to the previous arrangement where the Commonwealth of Massachusetts provided "unlimited" funding after the fact. By subsequently developing a SGR database, the MBTA was able to characterize the scale and scope of the SGR challenge and backlog, which has led to approximately 95% of funding being spent on SGR in recent years. Based on this analysis, the MBTA has an existing backlog of $2.7 billion. The agency has committed to investing $470 million per year in rehabilitation and replacement, which will keep up with normal replacement needs but not reduce the overall backlog. Under this new approach, the Commonwealth of Massachusetts has agreed to provide funding for system expansion projects, but the MBTA is responsible for ongoing maintenance, replacement, and operations. The SGR database provides the information necessary to prioritize investments within this constrained funding context. As described elsewhere, the MBTA is working to upgrade the database to be able to characterize the impact of capital investment decisions on the operating budget.

Desmond, K. "King County Metro Transit." Presented at the FTA CEO Panel of the 2008 Annual Meeting of the American Public Transportation Association, 2008.

This presentation describes King County Metro's Transit Asset Management Program (TAMP). The agency maintains a revenue fleet replacement fund that reserves money for the normal and ongoing replacement of the revenue fleet over the long-term. The agency implemented the TAMP to help maintain existing assets so that they can accomplish the purpose for which they were constructed or purchased. An annual facilities condition report is developed that summarizes the condition of these assets, recommends actions, and develops cost estimates and schedules. The TAMP supports development of the annual budget and the 6-year financial plan. The presentation also notes King County's initiative to implement sustainability initiatives, as well as the challenges and opportunities in implementing an asset management approach.

U.S. DOT. *Letter to Chairman of the Committee on Appropriations of the United States Senate Establishing a Definition of State-of-Good-Repair on Amtrak's Northeast Corridor.* U.S. DOT, 2008.

This letter from the Secretary of Transportation to a federal legislative committee with transportation oversight responsibilities provides the definition for SGR on Amtrak's Northeast Corridor. The definition is "A condition in which the existing physical assets, both individually and as a system, (a) are functioning as designed within their useful lives and (b) are sustained through regular maintenance and replacement programs; state of good repair represents just one element of a comprehensive capital investment program that also addresses system capacity and performance." The letter also provides definitions for terms used in this definition of SGR, and background on the process followed to develop the definition.

Amtrak. *Northeast Corridor State of Good Repair Spend Plan.* 2009.

Amtrak prepared this capital plan in response to Section 211 of the Passenger Rail Investment and Improvement Act of 2008, which required it to achieve an SGR by 2018 for Amtrak-owned portions of the Northeast Corridor main line and its branches, including the Springfield, Harrisburg, and Albany lines. However, Amtrak discusses the major engineering needs and operational challenges that make meeting this requirement impractical and infeasible. It makes a case for dividing the work needed over a greater span of years to maintain traffic flows and allow allocation of resources to non-SGR projects. It provides the annual spending needed to address the backlog of investment needs and sustain SGR by 2023. During this period, Amtrak proposes to spend nearly $12 billion or an average of $821 million per year for SGR.

Boylan, C. "The View from the Subway: The Challenges of Maintaining a 100 Year Old System." Presented at the 88th Annual Meeting of the Transportation Research Board, 2009.

This presentation provides a general overview of the MTA's ongoing efforts to return the system to a state of good repair, following the fiscal crises and disinvestment of the 1970s. SGR is defined as "investments necessary to correct for past deferred maintenance or to replace equipment that is beyond its useful life," with the further explanation that some include "normal replacement" as part of definition since it's essential to maintain SGR. The MTA's investments in SGR have grown over the years through ongoing capital programs, and the agency has made substantial progress in returning the system to a state of good repair, although there is still a significant backlog, particularly for New York City Transit. This has then led to significant improvements in performance and reliability, with associated ridership growth. Developing the capital program that has led to these improvements started with an asset inventory and condition assessment, which then led to the 20-year needs assessment and the 5-year (typically) capital program for the MTA. Paying for this work is described as a challenge requiring both traditional and innovative funding approaches.

FTA. *Rail Modernization Study.* Report to the United States Congress. FTA, 2009.

In response to a request from the U.S. Senate, in 2009 FTA completed a report that analyzes and assesses the level of capital investment required to attain and maintain a state of good repair among the nation's seven largest rail operators: Chicago Transit Authority (CTA), MBTA, the Metropolitan Transportation Authority (MTA, including all three rail operating agencies), New Jersey Transit (NJT), the Bay Area Rapid Transit District (BART), the Southeastern Pennsylvania Transportation Authority (SEPTA), and the Washington Metropolitan Area Transit Authority (WMATA). Together, these agencies represent approximately two-thirds of the nation's total investment in rail transit assets and 80% of the nation's daily rail ridership.

The report estimates the current backlog of SGR needs, and places those investment needs within the context of existing and potential future federal funding programs that support this type of reinvestment. The overall study results are that over one-third of the assets of these agencies are in marginal or poor condition and that the current backlog of SGR needs for these agencies is approximately $50 billion. Although these agencies have seen overall increases in their funding under the Section 5309 Fixed Guideway Modernization Program, they are receiving a smaller proportion of the funding available, because of the growth of new fixed guideway systems that have become eligible for that funding. Other federal sources of capital funding for rehabilitation and replacement include Section 5307 Urbanized Area Funds and Section 5309 and 5318 Bus and Bus Facilities Funds.

In 2006, the agencies studied spent $5.4 billion on rehabilitation and replacement, which is less than the $5.9 billion per year that is required simply to handle normal replacement of assets currently in a state of good repair, much less begin reducing the $50 billion backlog, which suggests that the SGR backlog is increasing. Beyond these basic numbers, the study includes more detailed breakdowns about the condition of these agencies' assets by mode. The study estimates that an annual investment of $8.4 billion is required for these agencies to eliminate the SGR backlog over the next twenty years, while also replacing current assets as they reach past the end of their useful life.

The study was completed using FTA's TERM, a tool that is used to estimate transit capital investment needs over a 20-year time frame, based on asset data collected by and reported to FTA. TERM is also used to support preparation of U.S. DOT's bi-annual *Report to Congress on the Condition and Performance of the Nation's Highways, Bridges, and Transit.* As a result, this model has been thoroughly tested, refined, and validated, and the results are consistent with other similar analyses that have been produced. In addition, the results were reviewed and validated by representatives from the transit agencies studied, and were also compared to the capital program estimates produced by these agencies. TERM rates assets on a scale of 5 (excellent condition) through 1 (poor condition), and an asset is considered to be in a state of good repair if it has condition rating at or above the midpoint of 2.5. TERM uses asset deterioration curves (based on empirical experience) to model the condition of assets over time.

Most of the agencies studied in the report have developed an asset inventory, and those that are not that far along are in the process of planning for or developing one. There are obviously differences in how each agency treats its inventory and the information that is included, but these inventories provide a good basis for this analysis. In developing the cost estimates for replacement and rehabilitation, FTA sought out unit cost data from individual transit agencies; where such local data was not available, unit costs from completed projects were used instead. In addition to the direct construction costs, additional soft costs were added, including planning/design, project management, and other contingencies. The estimates were done in constant 2008 dollars, without any adjustment for inflation.

The study also provides some information about current asset management practices at these agencies. As mentioned earlier, all of the agencies have asset management systems in place, although they vary in terms of comprehensiveness and sophistication. In one case, the asset management system is maintained by the MPO, not the agency itself. Not all of the agencies maintain a condition assessment of the assets in that inventory, and only one agency maintains comprehensive information about prior rehabilitation activities. In addition, only two of the agencies maintain information about the replacement costs for the individual assets contained in the inventory. In terms of using decision support tools to estimate SGR investment needs, only the MBTA currently maintains a database for this purpose, and the agencies tend to rely on informal or simple needs-based analyses to prioritize investments across assets given constrained funding.

Laver, R. "Defining and Measuring State of Good Repair." Presented at the 88th Annual Meeting of the Transportation Research Board, 2009.

This paper discusses a range of issues related to SGR. It describes different definitions of SGR used in U.S. transit agencies. It presents estimates of the percent of assets predicted to be in a state of SGR in the United States by asset categories based on figures generated using TERM, and discusses different measures that can be used to characterize SGR. These include percent of assets in SGR, percent of service life remaining, asset condition ratings, and asset-specific measures, such as pavement roughness, Mean Time/Distance Between Failures, and other measures.

Libberton, S. *Making a Federal Case Out of State of Good Repair.* Presented at the 2009 Rail Conference of the American Public Transportation Association, Chicago, IL, 2009.

This presentation outlines FTA's efforts to focus federal attention on SGR issues, including the 2008 CEO panel, the first SGR roundtable, and the Rail Modernization Study, which has started to characterize the magnitude of the problem. FTA is also developing training courses and has assembled relevant materials in a single location on their web site. The FTA also sponsored a national and international review of asset management approaches, which is one of the backbones of dealing with the state of good repair problem. FTA is also considering possible federal funding for SGR, including use of the Fixed Guideway Modernization funds and creation of a dedicated SGR funding pool.

Giuffre, W., Robert, W. and Hussey, L. "State of the Art in Evaluating State of Good Repair." In *Rail Conference 2009 Proceedings.* APTA, 2009.

This paper discusses different definitions for SGR. Most existing definitions involve meeting a certain level of service; performing maintenance, repair, rehabilitation and renewal according to a considered agency policy and/or reducing or eliminating a backlog of unmet capital needs. The authors propose the following definition of SGR: "a state that results from application of transportation asset management concepts in which a transit agency maintains its physical assets according to a policy that minimizes asset life cycle costs while avoiding negative impacts to transit service." The paper describes best practices in transit asset management, and provides a case study discussing the Virginia Department of Rail & Public Transit (DRPT) Program Guidance and Grant Evaluation System (PROGGRES), used to analyzing transit investment needs for DRPT.

Peskin, R.L. and Antos, J. "Asset Management and Preventive Maintenance: Setting Priorities to Improve Efficiency." Presented at the 88th Annual Meeting of the Transportation Research Board, 2009.

This presentation is primarily focused on presenting the MBTA's SGR database, detailed in other references included in this review. The presentation shows results obtained through applying the approach used for the MBTA database to a different transit agency, with a variety of different investment scenarios to demonstrate the impacts of increasing SGR funding, including reduced backlog and improved asset conditions.

Tuccillo, R. "State of Good Repair: Urban Transit Maintenance and How to Pay for It." Presented at the 88th Annual Meeting of the Transportation Research Board, Washington, D.C., 2009.

This presentation defines SGR as maintaining physical assets to support quality transit service, including managing assets effectively, replacing worn-out equipment, performing preventive maintenance, and upgrading facilities. FTA has developed TERM to aid in the measurement of SGR and predict the first-order impacts of investment decisions. The presentation discusses the possibility of a federal SGR program. Various innovative financing options are also available, including public-private partnerships, the Transportation Infrastructure Finance and Innovation Act (TIFIA) program, and infrastructure banks. The presentation notes that FTA is interested in improving asset management as a key prerequisite to addressing the SGR problem, and has taken steps such as developing TERM Lite for use by individual agencies, sponsoring research into asset management, and promoting the use of state of the art tools.

Arkin, Y. "Contribution of RAMS Specifications to State of Good Repair (SGR)." Presented at the APTA 2010 Rail Conference. APTA, 2010.

This presentation presents a definition of what constitutes a state of good repair based on the modeling approach in

TERM. It discusses the relationship between system reliability and preventive maintenance, and discusses the impacts of a strategy of allowing transit components to fail, ranging from increased deterioration to reduced ridership. Also, the presentation details the relationship between system availability, a measure of reliability, and the measures of mean time between failures (MTBF) and mean time to repair (MTTR). The presentation concludes by recommending that reliability, availability, maintainability and safety (RAMS) specifications be incorporated in contract specifications, and provides examples of such specifications.

Booz Allen Hamilton. *Transit Economic Requirements Model User's Guide.* Version 2003.1. FTA, 2010.

This guide details the modeling approach and use of the FTA's TERM. TERM is a software application designed to estimate the capital investment needed to maintain or improve the nation's transit infrastructure over a 20-year period and forecast the physical condition of transit assets. The guide describes the research, theories, assumptions, and formulae behind TERM and provides instructions on how to use its six analytical modules: Rehab-Replacement; Asset Expansion; Operating Speed Performance Enhancement; Vehicle Occupancy Performance Enhancement; Benefit–Cost of Rehab/Replace and Asset Expansion Investments; and Benefit–Cost of Performance Improvement Investments. The document provides guidance on running and maintaining TERM, as well as on the data requirements and input parameters for analyzing various investment scenarios.

Flanigon, M. "Deferred Maintenance Impact on Safety." Presented at the APTA 2010 Rail Conference. APTA, 2010.

This presentation describes the increase in accidents that has occurred in the rail industry between 2003 and 2008, noting that accident rates increased from 2.97 to 5.35 accidents per 100,000 passenger miles. It discusses the relationship between deferred maintenance and safety, and notes the need for increased spending to achieve SGR. Also, the presentation presents lessons learned from the NTSB report on the CTA derailment in 2006, attributed by NTSB in part to deteriorated infrastructure, and notes the safety implications of SGR.

FTA. *National State of Good Repair Assessment.* Report to the United States Congress, FTA, 2010.

Following up on the 2009 *Rail Modernization Study,* FTA produced a broad state of good repair assessment for the U.S. transit industry as a whole (including all known transit assets), at the request of Secretary of Transportation Ray LaHood. The assessment concludes that there is an estimated $77.7B (2009 dollars) backlog of state of good repair needs, and that an annual investment of $14.4 billion is required to keep that backlog from getting larger. Based on the analysis using the Transit Economic Requirements Model, approximately one-third of the nation's transit assets are in poor or marginal condition, and only 30% are in good or excellent condition. TERM uses asset deterioration curves to rate assets on a scale of 5 (excellent condition) to 1 (poor condition), and an asset is considered to be in a state of good repair if its condition is rated above the midpoint (2.5). The study notes that there is no generally accepted definition of state of good repair, with definitions varying across agencies, if they have even developed a definition.

To validate and adjust the results produced by TERM, the results were compared to current unconstrained needs estimates from a number of large transit agencies. Staff from various agencies were involved in reviewing the process and results. Because detailed asset inventories are not readily available for every operator in the country, FTA obtained detailed data from certain large and medium agencies, including the seven agencies included in the *Rail Modernization Study* and 16 other agencies that were contacted directly for this study. For other agencies, data available from the National Transit Database was used to estimate the assets and their condition. This process illustrates some of the data availability challenges that exist in characterizing and addressing state of good repair issues. Based on the number above, FTA suggests an annual investment in state of good repair activities of $18.3 billion, which will achieve a state of good repair within 20 years while continuing normal replacement. However, recent annual investments in repair, rehabilitation, and replacement have been approximately $12 billion to $13 billion, which is not even enough to keep up with current normal replacement needs. At this continued rate of funding, the backlog will continue to grow. The study estimates that by 2030, close to 30% of transit assets will be beyond their useful life. It's worth noting that the construction cost estimates are adjusted to reflect "soft costs" such as project management, design, and the cost of replacing assets while they are in active use.

Of the 16 transit agencies that were contacted for detailed information, only one currently has an asset management system in place, although many of these agencies are in the process of developing one or have formally acknowledged the need for one. Only a limited number of agencies have made a commitment to performing a regular asset condition inventory, and only one agency maintains a decision support tool that allows for the analysis of the outcome of different investment scenarios. There are also a wide variety of approaches to investment prioritization, ranging from focusing on mission critical elements, to safety, to maintaining historic levels of investment. Only two agencies use an objective tool to prioritize investments.

The report also provides a summary of asset management techniques and the status of asset management in U.S. transit agencies. A description and case study related to the Governmental Accounting Standards Board (GASB) Statement 34, which provides a framework for how governments report their finances, and requires the inclusion of information relating to capital assets and their life cycle costs. The report concludes with a description of FTA's planned activities to support SGR and asset management, including training courses, the SGR working group and roundtables, grant incentives, the development of TERM Lite for use by individual transit agencies, and the possible development of a national transit asset inventory as part of the National Transit Database.

FTA. *Transit Asset Management Practices: A National and International Review.* FTA, 2010.

This report defines SGR as "a state that results from application of transportation asset management concepts in which a transit agency maintains its physical assets according to a policy that minimizes asset life cycle costs while avoiding negative impacts to transit service." It reviews FTA publications on SGR analysis, literature on transit asset management practices at selected agencies, and available models and frameworks to implement SGR concepts. It provides case studies on existing SGR practices at U.S. and international transit agencies and U.S. state DOTs. Also, the report summarizes representative current practices and state-of-the-art practices in seven subject areas related to asset management, and compares practices in six functional areas for six agencies interviewed as part of the research.

General Accounting Office (GAO). *Federal Transit Programs: Federal Transit Administration Has Opportunities to Improve Performance Accountability.* Report to the United States Senate. GAO, 2010.

At the request of the U.S. Senate's Committee on Banking, Housing, and Urban Affairs, the GAO developed a report analyzing how federal transit programs could be made more performance-based. The GAO analyzed eight of the eighteen FTA funding programs, including two that are directly related to SGR: the Fixed Guideway Modernization Program (FGMP) and the Bus and Bus Related Equipment and Facilities Program (Bus Facilities Program). Given that the goal of SGR programs is ultimately to improve the performance and reliability of the nation's transit systems, making these program more performance-based is potentially an important related goal for the FTA's overall SGR efforts. The report analyzed the following types of measures:

- Process-oriented measures that address the type and level of program activities conducted;
- Output-oriented measures that address the direct products and service delivered by the program; and
- Outcome-oriented measures that address the results of these products and services.

For the Bus Facilities Program, funding had typically been allocated directly by Congress, based on a variety of priorities and political considerations. In 2007, FTA allocated the funding partly based on performance, measured by ridership and bus loading. In addition (but not mentioned in this report due to timing), the most recent allocation of Bus Facilities funding was prioritized specifically for SGR activities, based on a variety of projected benefits. The FGMP is allocated purely based on a formula that takes into account route miles of guideway and revenue vehicle miles. However, even for programs where FTA awards funding based on performance, there is little or no attempt to connect that funding to future outcomes, or to base future funding on the performance impacts of previous investments. Therefore, the GAO report suggests that FTA adopt a system of financial and non-financial incentives to promote improved performance by grantees, potentially measured in a variety of different ways. Within that recommendation, the GAO acknowledges that different programs lend themselves better and worse to being performance-based, depending on the structure and goals of the program.

International Transit Studies Program. *Research Results Digest 95: Report on the Spring 2009 Mission - Performance Measurement and Outcomes.* Transportation Research Board of the National Academies, Washington, D.C., 2010.

This report summarizes the findings from TCRP Project J-03, "International Transit Studies Program," a mission conducted by a team of fourteen U.S. professionals from large and small transit systems to study transportation in four cities in four Southeast Asian countries in 2009. The team traveled to Hong Kong, where they studied the Hong Kong Transport Department, Kowloon Motor Bus (KMB) Company, and Hong Kong Mass Transit Railway (MTR); Singapore, where they studied the Land Transport Authority (LTA), Public Transport Council (PTC), and Singapore Mass Transit Rail Corporation (SMRT); Kuala Lumpur, where they studied RapidKL; and Taipei, where they studied the Taipei Rapid Transit Corporation (TRTC). For each city, the report provides the history, political structure, and approaches to planning. The report describes the team's observations of these agencies: how performance data are collected, verified, analyzed, used to relate to agency goals and objectives, and implemented to refine decision making; how performance measures are determined and used to improve customer service and inform appropriate parties; and how service contracts reward performance.

Long Beach Transit. *Maintenance Department Policies and Procedures Manual.* 2010.

This manual establishes the policies and procedures that Long Beach Transit Maintenance Department employees are required to follow to conduct preventive and unplanned maintenance activities. It is organized into the following sections: fleet maintenance, utilities, quality assurance, facilities, stops and zones, maintenance administration, and warehouse operations. It describes the details involved in procuring, inspecting, managing, repairing, and disposing equipment.

MBTA. *Capital Funding Request for Inclusion in the FY12–FY16 Capital Investment Program.* 2010.

This document is the form to be completed by MBTA departments to submit a project for inclusion into the 2012–2016 Capital Investment Program. Respondents indicate the category of the project, project description and scope, impact to the environment, impact on state-of-good-repair, impact on operations, legal requirements, alternatives, impact on the operating budget, consequences of not funding the project, and the conceptual budget and schedule.

MBTA. *FY12–FY16 Capital Investment Program Scoring Criteria.* 2010.

This document provides the scoring guidelines for candidate projects for the MBTA Capital Investment Program for 2012–2016. Projects receive scores based upon the severity of the health and environmental deficiencies they correct, the condition of the assets they address, operational and fiscal impacts, and urgency in meeting legal commitments.

Ryus, P., Coffel, K., Parks, J., Perk, V., Cherrington, L., Arndt, J., Nakanishi, Y., and Gan, A. *TCRP Report 141: A Methodology for Performance Measurement and Peer Comparison in the Public Transportation Industry.* Transportation Research Board of the National Academies, Washington, D.C., 2010

This report provides guidance on selecting performance measures and benchmarks appropriate to a transit agency's particular areas of concern, mode, and size. It proposes that transit agencies perform benchmarking by contacting top-performing peers to learn from them and setting goals or targets for performance improvement. The report describes an eight-step methodology to implement this approach, which has been incorporated into the Florida Transit Information System (FTIS) online tool: understand the context of the benchmarking exercise; develop performance measures; compare performance within the peer group; contact best-practices peers in areas where one's performance can be improved; develop a strategy for improving performance based on the best-practices; implement the strategy; and monitor changes in performance over time. Agencies can use the report's list of nationally available measures with standardized data and FTIS to identify potential peers and investigate their area of interest. The report also provides case studies on these agencies that used the proposed methodology to address a variety of performance questions: Altoona Metro Transit, Knoxville Area Transit, Utah Transit Authority, Denver Regional Transportation District, Santa Clara Valley Transportation Authority, and South Florida Regional Transportation Authority.

Transport for London. *Transport for London Investment Programme 2010: London Underground.* Transport for London, 2010.

This report provides information on London Underground projects that cost more than £5m for the period between 2010 and 2018. For each project, it describes the purpose, project status, deliverables, expended spending levels for each fiscal year, and milestones. It also describes how each project contributes to the Mayor of London's transportation priorities, which include objectives to improve capacity, connectivity, the journey experience, state-of-repair, cost-efficiency, safety, and environment.

Kozuki, A., Marceron, A., Ames, L. and Antos, J. "Projecting Asset Conditions and State of Good Repair Considering Multiple Transit Agency Corporate Goals." Presented at the 90th Annual Meeting of the Transportation Research Board, 2011.

This presentation provides an overview of transit asset management concepts and describes an effort to improve capital investment decision making through SGR analysis for San Francisco MUNI by AECOM and Decision Lens. It covers the asset management framework, its benefits, and the questions it answers. It describes how the focus on SGR by FTA and Metropolitan Transportation Commission (MTC) has provided impetus to the MUNI to better link asset condition to service improvements. It provides the MUNI's current state of repair needs, the replacement value of the assets, and the SGR backlog. Further, it details three quantitative approaches to prioritizing capital projects currently considered by MUNI. They include scoring and ranking projects based upon how well they meet goals and criteria (using the Decision Lens software), using the asset age (from the MBTA SGR Database, adapted for MUNI use), and using a combination of project scores and asset age. The presentation describes the impact of using them. It also presents scenarios for low, middle, and high funding levels to determine how funding levels change asset conditions, average fleet age, and SGR backlog.

MARTA. *FY2012 Capital Budget Call Package.* MARTA, 2011.

This document was prepared to assist Metropolitan Atlanta Rapid Transit Authority (MARTA) departments in submitting capital projects for inclusion into the 10-year Capital Improvement Program (CIP). It contains instructions for completing and submitting information, a description of the capital budgeting process and its timeline, names and contact information for the support team members and decision makers, and the policies and procedure to be followed to gain approval and authorization.

Tepke, G., Grant, Y., Laver, R. "Regional Transit Capital Inventory – Phase 2." Presented at the 90th Annual Meeting of the Transportation Research Board, Washington, D.C., 2011.

This presentation describes the Regional Transit Capital Inventory (RTCI) project of the Metropolitan Transportation Commission and Booz Allen Hamilton. The RTCI was developed to project the needs of transit agencies in the San Francisco Bay Area in the Regional Transportation Plan and inform need-based funding allocation. Phase 1 of the RTCI, which has been completed, involved inventorying the assets owned by operators and established standard costs and life cycles for those assets. Phase 2, which is in progress, would refine cost and asset data and enable operators to use the RTCI for their process improvements. Work that remains to be done include tying state-of-good-repair investment actions to service performance, ridership, and environmental impacts.

Saaty, D. "Prioritization in Transportation Capital Programming." Presented at the 90th Annual Meeting of the Transportation Research Board, 2011.

This presentation describes an effort to improve capital investment decision making through SGR analysis for San Francisco MUNI by AECOM and Decision Lens. It proposes the Structured Decision Making Process to resolve multi-criteria decision problems created by competing interests such as ridership, maintaining and preserving assets, environment, costs, and partnerships. The process involves identifying issues and framing them in a hierarchy, and building a group consensus on their relative importance to prioritize them. The presentation describes how a group of decision makers can rate projects according to these criteria in the Decision Lens software, which would recommend allocation amounts to provide the highest return. The presentation concludes with benefits of this approach, which include capturing institutional expertise and knowledge.

Springstead, D. "Asset Management: An Agency Perspective." Presented at the 90th Annual Meeting of the Transportation Research Board, Washington, D.C., 2011.

This presentation chronicles the history of asset management at the Metropolitan Atlanta Rapid Transit Authority (MARTA). In the 1990s, MARTA implemented the New Maintenance Management Information System (MMIS), but its limitations in functionality led to variations in how it was used and poor asset data quality. In 2006, MARTA acquired an enterprise asset management system to improve its records on its assets. MARTA used the Life Cycle Asset Rehabilitation Enhancement (LCARE) process to identify assets. In 2010, efforts to remediate the database led to completing information on assets already in the database and adding the assets that were missing from the database. However, severe budget cuts in recent years are expected to dramatically increase MARTA's SGR backlog. The presentation discusses some of the largest capital needs faced by MARTA.

Edrington, S. and Brooks, J. *Impacts of Funding and Allocation Changes on Rural Transit in Texas-Final Report.* University Transportation Center for Mobility, June 2011.

This report presents research on the impact of changes in funding and allocation formulas on the provision of transit service by Regional Transit Districts (RTDs) in Texas, comparing time-series data as these changes took place. The two major changes that took place over the time period that was studied were a significant increase in federal funding for rural transit resulting from the Safe, Accountable, Flexible, and Efficient Transportation Equity Act (SAFETEA) passed in 2005 and changes in allocations of state and federal funding as Texas DOT implemented a needs- and performance-based allocation formula. The changes in the allocation formula resulted in certain winners and losers among the RTDs, although certain rate-limiting safeguards were put in place to mitigate any large year-over-year changes in allocations. Most of the funding available under these programs is used for operating expenses (broadly defined), although it can also be used for capital expenses, with a lower local match requirement. As a result, the applicability of this research to state-of-good-repair and asset management issues is limited, although there are more general lessons to be learned about the expenditure of federal funds and the agency responses to changes in funding levels and allocations.

One of the key conclusions of the report is that while federal funding was increasing substantially over this period, the changes in allocations of state funding made it difficult for RTDs to provide the required local match, since they rely heavily on the state funding to provide the required match (which is set at 50% for operating expenses). Of the 38 RTDs in Texas, 36 were able to fully match their federal funding allocations with state funds in fiscal year 2008, while by fiscal year 2010, state funding levels had declined to the point where only nine RTDs were able to fully match their federal funding using state funds. Although this led to additional creativity in identifying sources of local funding, it also led to a shortfall of $5.3 million in the amount of state funds required to match federal funds. This shows how local and state funding sources must keep pace with any increases in federal funding, or else recipients will not be able to maximize the use of that funding. This is an important consideration for any future SGR funding program that FTA might consider, since cash-strapped transit agencies will need to identify local funding sources that can match those expenditures.

As part of the studies, the authors also examined how the RTDs responded to the changes in available funding, either positive or negative. Most agencies invested additional funds in providing additional service, but many also used it as a way to improve technology (by installing automatic vehicle location or mobile data terminal systems) or to purchase new vehicles. Similarly, the most common response to reductions in funding was to reduce service, but agencies also chose to defer purchases of vehicles, equipment, or new technology, or at least look for ways to reduce these costs. RTDs were also forced to respond to "external" changes in costs, particularly in terms of fuel costs, employee benefits, and insurance, and responding to these changes often consumed much of the new funding, or made it even more challenging to respond to funding reductions. The research also found the expected result that increases in service levels led to increases in ridership. However, the rate of increase in ridership was lower than the rate of increase in service levels/revenue hours, most likely because the services being added were more marginal and less productive than the services already in operation. Similarly, decreases in service levels led to smaller percentage decreases in ridership, as less productive routes were typically cut first.

International Transit Studies Program. *Research Results Digest 101: Funding for Infrastructure Maintenance: Achieving and Sustaining a State of Good Repair.* Transportation Research Board of the National Academies, Washington, D.C., 2011.

This report summarizes the findings from TCRP Project J-03, "International Transit Studies Program," regarding a mission conducted by a team of seventeen U.S. professionals from large and small transit systems to study state of good repair issues in six cities in four countries in Europe in 2010. The team traveled to: Great Britain, where they met with agencies in London and Nottingham; Germany, where they met with agencies in Berlin and Karlsruhe; Strasbourg, France; and Oslo, Norway. Topics addressed in the meeting included definition and measurement of state of good repair, prioritization of capital investments, funding, public-private partnerships, political and community involvement, training and personnel, and tracking and prioritizing inventory and maintenances. Three presentations described below from the 2010 FTA State of Good Repair Roundtable present results for the mission. These include "International Transit Studies: Tools and Systems," "International Transit Studies: State of Good Repair Definition and Measurement," and "Funding & Finance for State of Good Repair in European Transit Systems."

B.3 FTA State of Good Repair Summits and Roundtables

FTA. *Transit State of Good Repair: Beginning the Dialogue.* FTA, 2008.

FTA issued this report summarizing the Summer 2008 State of Good Repair Summit, which was also intended to set the stage for the additional work that has followed, including the two roundtables and ongoing research efforts. As such, this document attempts to summarize much of the information that was discussed at the summit and point towards future directions. The report begins by defining the SGR problem: although federal, state, and local funding in the amount of $165 billion has been devoted to repair, rehabilitation, and replacement of transit assets since 1991 (when ISTEA was passed), the condition of the nation's transit assets continues to decline, with spending only at 60% to 80% of what is required to eliminate the backlog of deferred maintenance and perform ongoing normal replacement. This lack of expenditure manifests itself in poor service reliability and aging facilities, which in turn depress ridership. Estimates made at the time by FTA using TERM show that roughly ¼ of transit assets nationwide are in poor or marginal condition, while ⅓ of the assets of the nine largest rail agencies are in poor or marginal condition. The report also points out that as new heavy and light rail systems have come on line over the past 20 years, the size of the Fixed Guideway Modernization Program (the primary source of SGR funding for rail systems) has not increased at the same rate, meaning that each agency is getting a smaller share of the pie. This underinvestment also has serious safety consequences, as demonstrated by a number of rail accidents in recent years that can be attributed (at least partially) to deferred maintenance, such as an accident on

Chicago's Blue Line heavy rail in July 2006. These types of safety concerns extend beyond transit into other transportation modes that suffer from deferred maintenance.

In response to this situation, FTA convened the State of Good Repair Summit that forms the basis for this report, as well as created an internal SGR working group and initiated the Rail Modernization Study requested by Congress (reviewed elsewhere in this document). In addition, FTA proposed to undertake a variety of additional activities, many of which subsequently occurred or are underway, and are described and reviewed elsewhere.

The remainder of the report summarizes the proceedings of the roundtable, which are mostly summarized in the presentations reviewed below. However, additional information and insights contained in the report include:

- The summit included participants from the nine operating agencies included in the *Rail Modernization Study,* as well as from several other agencies.
- For rail systems, the assets most likely to be at or past their useful life are vehicles and stations (primarily subway stations), while for bus systems, maintenance facilities and vehicles have the greatest proportion of assets in poor condition.
- A comparison between the results produced by TERM and those produced by the MTA (New York State) and the MBTA shows that there is a reasonably good (although still somewhat rough) correspondence between the estimated proportion of assets that are past their useful life. The discrepancies that do exist are likely related to differences in defining an asset's useful life.
- In general, there is not significant experience with predicting the impact of asset conditions on system performance. This is due to both a lack of data and a lack of analytical tools, although there is general agreement that poor maintenance and rehabilitation will lead to reduced performance on a variety of metrics (i.e., on-time performance, service availability, comfort).
- A number of the agencies mentioned that simply estimating the in-kind replacement of assets may be misleading, since there are often betterments required as part of normal replacement, such as making a station ADA-compliant, that are not reflected in these estimates. In addition, there is often a need to replace an asset due to technological obsolescence, even if the asset is still within its useful life.
- A number of measures of SGR are proposed, including percent of assets in a state of good repair, percent of service life remaining, and asset condition ratings (both general and asset-class specific). The pros and cons of the different possible measures are described and summarized.
- The report includes a discussion of preventive maintenance concepts and the relationship between PM and SGR, particularly in terms of extending the life of an asset. Most transit agencies currently maintain a maintenance management system, particularly for rolling stock/vehicles (both revenue and non-revenue), and every agency has a preventive maintenance program of some type.

AECOM and FTA. "FTA State of Good Repair Summit: Working Session Presentations." Presented at the 2008 FTA State of Good Repair Summit. FTA, 2008.

The presentation from the summit provides an outline and discussion guide for the summit. The materials focus primarily on framing a set of discussion topics and issues to be addressed, rather than a more didactic presentation of materials. Key points related to the TCRP Project E-09 research effort include:

- TERM modeling at the time indicated that annual reinvestment needs for heavy rail and bus were approximately the same, at just under $4 billion/year each. Light rail systems have the lowest reinvestment needs, because of the limited number of systems and their relatively recent construction (other than the legacy trolley systems). TERM also estimated that the asset classes with the greatest percentage of assets not in a state of good repair are signals, communication, rail stations, and revenue vehicles.
- The presentation raises several issues regarding the relationship between preventive maintenance and state of good repair, particularly whether improved PM can result in lower SGR needs, the relationship between PM, asset condition, and asset management approach, and whether a strong PM program is a necessary condition for achieving a state of good repair.
- The presentation summarizes SGR definitions from several different transit systems:
  - Chicago CTA: Defines SGR primarily in terms of standards:
    - Rail lines should be free of slow zones and have reliable signals;
    - Buses should be rehabbed at 6 years and replaced at 12 years;
    - Rail cars should be rehabbed at quarter- and half-life intervals and replaced at 25 years; and
    - Maintenance facilities should be replaced at 40 years (70 years if rehabbed).
  - Cleveland RTA: State of good repair projects are those needed to bring the system to a consistent, high quality condition system-wide.
  - MBTA: A state of good repair standard [is where] all capital assets are functioning at their ideal capacity within their design life.

- New Jersey Transit: State of good repair is achieved when infrastructure components are replaced on a schedule consistent with their life expectancy.
- MTA New York City Transit: Investments that address deteriorated conditions and make up for past disinvestment.
- SEPTA: An asset or system is in a state of good repair when no backlog of needs exists and no component is beyond its useful life. SGR projects correct past deferred maintenance, or replace capital assets that have exceeded their useful life.

- The presentation then provides an operational definition of SGR: "An asset or system is in a state of good repair when no backlog of capital needs exists—hence all asset life cycle investment needs (e.g., preventive maintenance, rehab, replacement) have been addressed and no capital asset exceeds its useful life."
- The presentation then discusses asset management principles, and the fact that many U.S. transit agencies view asset management as simply good maintenance management. A broader, more inclusive definition of asset management is then proposed: "Transportation Asset Management is a strategic and systematic process of operating, maintaining, improving and expanding physical assets effectively throughout their life cycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision making based upon quality information and well-defined objectives." Asset management is then described in broad terms, along with an overview of current transit asset management tools in the United States, particularly FTA's TERM.
- Additional topics discussed as part of the summit included:
  - The relationship between SGR and core capacity improvements for rail transit systems, which refers to capacity enhancements in the most heavily used segments of the system, aimed at ensuring the ability to comfortable, reliably, and efficiently serve the urban core. This then leads to the concept of "State of Good Performance," which takes into account both the condition of an asset and its ability to adequately serve travel demand (arguably, this is similar to the difference between structurally deficient and functionally obsolete in bridge ratings).
  - SGR and asset management research needs, including connections to similar research for other modes.
  - Various traditional and innovative funding arrangements, including the pitfalls that may be present with some of the more innovative techniques.

Barnes, D. "Foothills Transit State of Good Repair." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation discusses the approach to achieving a SGR used by Foothills Transit. Foothills Transit is a medium-size transit operator serving the area east of downtown Los Angeles. It is a bus-only system that was established a little over 20 years ago, and uses a private-sector service management and operations model, employing multiple operating contractors. Because of the structure of the system and the private contracting model, the main focus of maintenance and state of good repair is setting performance standards and ensuring that the contractors adhere to those standards. Because the contractors are tasked with—and measured by—service delivery, many of the asset management issues are simply transferred to the private contractors. The contracts are set up with both penalties for poor service (vehicles being unavailable, poor cleanliness) and incentives for good performance. In addition, there are quarterly maintenance audits performed by an outside vendor, as well as periodic inspections of facilities and vehicles.

Couch, D. "Washington Metropolitan Area Transit Authority Overview." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation provides a basic overview of the history and development of the WMATA system, including both heavy rail (Metro) and bus. The main point of the presentation is that WMATA's key assets on both the rail and bus side are beginning to reach the end of their useful lives, and are beginning to require more serious maintenance and replacement. WMATA is in a fairly typical situation where funding is outstripped by the capital needs, even leaving aside plans for new capacity/system expansion. The presentation provides information on operational and procurement strategies that are used to minimize the cost and impact of major rehabilitation work, particularly in terms of coordinating work schedules. WMATA's stated definition of SGR is that infrastructure components are replaced on a schedule consistent with their life expectancy.

Dawson, L. "Chicago Transit Authority: Asset Inventory Structure." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation describes CTA's efforts to build an asset inventory. CTA began a comprehensive engineering review of assets in 1992–1994, which created a comprehensive asset inventory that was used in a RIMS database, which is still in use for structural inspections. In 2001, they began a 20-year capital needs assessment using Capital Program Manager, which was updated on a rolling basis until 2008, when it was stopped due to funding constraints. The asset tables in this database are comprehensive across infrastructure and structures, but do not include revenue fleet, which is maintained in a separate MMIS database, or fare collection and communication data. These external data were in the process of being integrated into asset tables, a process which is presumably complete. The 20-year needs assessment also describes projects and their relationships to assets; the asset tables do not directly generate the projects, but are rather a reference in the development of the capital needs assessment and the estimate of the overall cost to maintain the system. Although CTA maintains a number of asset databases and was in the process of updating/enhancing them, the linkage between these asset databases and the development/prioritization of projects is relatively loose, with these databases used more as a reference point than as a detailed source of project development and prioritization.

Friem, R. "Scheduled Maintenance Interval: The Plan." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation describes the SGR efforts of the Bi-State Development Agency in St. Louis. Prior to the development of the Scheduled Maintenance Initiative program, the Bi-State Development Agency (Metro) had no plan for ongoing scheduled and preventive maintenance, and was experiencing a very poor mean distance between failures (MDBF), a lack of consistency in maintenance procedures, and long delays in bus repairs at its central maintenance facility. The presentation details the approach taken to resolve this problem, which included establishing a scheduled maintenance program, improving inventory and storeroom operations, resolving work-flow and communications issues, and enhancing training and management. Based on this intervention, the agency saw a dramatic improvement in MDBF and time in the shop, as well as reductions in maintenance and fuel costs.

Henley, D. "MTA New York City Transit Approach." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation summarizes the needs assessment approach used by New York City Transit (NYCT). As part of its Capital Needs Assessment process, NYCT performs a full asset condition inventory every five years. NYCT recently switched from a "legacy" approach that was developed in 1982 as part of the first MTA Capital Program, to an updated system which provides a more detailed view of the condition of assets and the need for repair/replacement. In particular, the new system assesses assets on a sub-asset/subcomponent basis, applies asset information regardless of the history or age of that asset, and weights asset condition and useful life information proportionally for each sub-asset to result in an overall score for each asset. As before, the system rates assets and sub-assets on a 1–4 scale, with categories 3 and 4 typically implying an investment need. The new system also takes into account that assets that have been brought into a state of good repair within the past 25 years are starting to fall out of good repair, which the previous system did not acknowledge. As a result of this change in the evaluation system, the condition rating for different types of assets has changed, typically resulting in an assessment that fewer assets than originally thought are in a state of good repair. Based on this revised approach, NYCT is now moving away from the "full rehabilitation" strategy that was used previously, where an asset was completely replaced/rehabilitated, regardless of the relative needs of the different components. Instead, they are focusing on rehabilitating specific components of stations or a set of stations, to ensure that the most critical or most degraded components are repaired in a timely manner, rather than waiting until funding is available to modernize the entire station. The presentation emphasizes the fact that as assessment tools and techniques become more sophisticated and powerful, the full power of that information should be used to make the best prioritization decisions on a more nuanced basis.

Laver, R. "Best Approaches to Building an Asset Management System." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation provides a broad definition of asset management, in terms of achieving strategic objectives, balancing competing needs across an organization and its various assets and needs, and using data and analysis to make informed decisions. Asset management is described as being a tool that can be used to achieve specific objectives, such as achieving a state of good repair. The presentation then provides a description and critique of current asset management practices in the transit industry, and then provides suggestions for how these practices might be improved. This is followed by a description of asset management as performed by highway agencies, including a conclusion that although the mix of assets is different for highway agencies, many of the same principles could be successfully applied to the transit industry. According to this presentation, the most successful asset management programs share the following characteristics:

- Have performance measures that guide investment decisions
- Adopt a "preservation first" strategy for their investment priorities
- Moved away from a "worst first" investment strategy
- Undertake scenario analysis showing the consequences on performance measures of various investment decisions
- Conduct an organizational self assessment as one of the most important starting points for implementing an asset management process
- Have an asset management champion

Some of the key challenges identified include integrating asset management into ongoing operations, in terms of both collecting data and using the data and analysis for decision making; developing support from management and letting staff know about that support; and dealing with general resistance to change. The presentation closes with a listing of the advantages of asset management, which include maximizing service performance and reliability, minimizing life cycle costs, making managers more accountable, being better positioned to obtain funding, improving safety, and meeting customer expectations.

Laver, R. "Transit Economic Requirements Model (TERM)." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation provides a general overview of FTA's TERM, along with a more detailed description of the Rehab-Replacement Module of TERM and the use of TERM in developing the Rail Modernization Study released by FTA. TERM is used to assess the physical condition of the nation's transit system and estimate investment needs for the future, in terms of both maintaining conditions and improving performance. It also provides a tool for analyzing the benefits and costs of proposed investments. TERM is used to produce various analyses and reports, including the transit sections of the U.S. DOT report "Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance." TERM functions by allowing the user to define investment scenarios based on maintenance and replacement of assets, budgetary constraints, and economic parameters, which then act upon a model database that represents the current status and context of U.S. transit systems. The model then produces estimates of investment needs required to maintain system performance, as well as estimates of future asset conditions, both of which can be used by government agencies to make capital programming and budget decisions.

TERM is inclusive of all transit assets, from facilities, to rolling stock, to systems. It is made up of six modules: four investment modules that analyze rehabilitation-replacement investments, asset expansion investments, crowding reduction investments, and speed improvement investments, and two benefit-cost analysis modules that analyze different types of investments. The rehab-replacement module produces estimates of investment needs on a yearly basis over a 20-year analysis time frame, along with predicted asset conditions over that same period. Developing these estimates requires a relatively high level of detail regarding existing assets, expected useful lives, decay patterns, and the impact of these assets decaying. Much of this information is either provided by asset manufacturers or has been developed empirically over time.

TERM uses a five-point scale to describe the condition of each asset and sub-asset, with 5 the highest score and 1 the lowest score; intermediate scores and break points are described in the documentation. The inventory covers the assets of over 600 urban and rural transit operators and includes approximately 400 different asset types organized in a hierarchical structure. In developing the ratings based on each sub-asset, the scores are weighted based on three factors: the contribution of the sub-asset to the overall life cycle cost of the overall asset, the safety implications of that sub-asset, and the appearance and level of comfort of the asset.

TERM was used to develop the investment needs estimates for the Rail Modernization Study published by FTA, which estimated the rail state of good repair needs for the nine largest rail operators in the United States, described previously in this review.

Moss, G. "National Bridge Inspection Standards." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation provides a detailed overview of the National Bridge Inspection Standards, including references to relevant laws and regulations, descriptions of bridge inspection procedures and requirements, training/certification, and use of the National Bridge Inventory database. Although most of the information in the presentation is very specific to the bridge inspection process, it does summarize the bridge inspection frequency requirements, which may be of use to transit asset managers. In general, bridges must be inspected every 24 months, although that can be extended to 48 months with permission from FHWA, while underwater structures must be inspected every 60 months (extendable to 72 months with FHWA permission). In both cases, there are procedures for establishing criteria that would require more frequency inspections. FHWA also now requires that Fracture Critical Members on bridges be inspected every 24 months, or more frequently based on criteria. Once these inspections have taken place, the results must be entered into the inventory within 90 days for state and federal bridges, and within 180 days for all other bridges.

Robert, B. "International Perspectives on Asset Management and SGR." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation summarizes the results of the FTA report ***Transit Asset Management Practices: A National and International Review*** described previously, focusing on review of international examples of transit asset management.

Rutledge, J. "King County Metro Overview." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation provides an overview of King County Metro's Transit Asset Management Program (TAMP), particularly for fixed assets (excluding the Seattle Bus Tunnel). The agency also has separate asset management programs for vehicles and IT assets. King County Metro has a full-time TAMP Program Manager and a TAMP Team made up of representatives from the various divisions within the agency that are responsible for assets. The TAMP has a mission statement to "preserve existing King County Transit plant and equipment to accomplish the purpose(s) for which they were constructed or purchased. Replace equipment and/or infrastructure as indicated by the facilities and equipment assessment, life cycle projections, condition inspections and maintenance reporting." The TAMP is organized into three replacement models that operate at the component and subcomponent levels:

- Facilities and Infrastructure, including large building systems.
- Equipment Replacement for items that can be swapped/replaced, as opposed to rehabilitated/modernized.
- Regular Asset Replacement, particularly for system elements.

The basic approach for asset inspection is that assets that are within 6 years of needing replacement/rehabilitation (based on the projected/assumed useful life) are inspected on a yearly basis. Based on these inspections, the available budget, and other factors, the TAMP team then develops an annual work plan. Since 1990, the TAMP program has been using CMMIS DataStream MP-2 for asset and maintenance record keeping, but was in the process of upgrading to Infor at the time of this presentation.

Shemaka, A. "National Bridge Inventory." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation provides a detailed description of the National Bridge Inventory, including coding of information and the types of data stored. Based on this information, the bridge can be rated as Structurally Deficient (load carrying elements in poor condition or waterway adequacy is insufficient), Functionally Obsolete (does not meet current geometric standards), Not Deficient, or Not Applicable (not a highway bridge). Based on inventory data, bridges are then assigned a sufficiency rating from 0 to 100, which makes bridges eligible for funding from the Highway Bridge Program. Bridges with a Sufficiency Rating of 0–49.9 are eligible for replacement, and those with a rating of 50–80 are eligible for rehabilitation. In this manner, the inspection information that is entered into the inventory leads directly to funding allocations and project prioritization. In addition, the inventory provides a basis for overall reporting on the health of the nation's bridges, on a local, state, and national level.

Springstead, D. "MARTA Asset Management Program." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

Based on this presentation, MARTA employs a fairly sophisticated asset management process that uses a high level of information as an input into the development of their CIP. 85% of the CIP is aimed at State of Good Repair activities. However, the most recent comprehensive asset inventory was performed in 2000, and at the time of this presentation, MARTA was planning to do another inventory in 2010 to allow for a comprehensive update to their CIP. The previous condition assessment uses an Asset Breakdown Structure with 16 major categories, and sub-categories below that. The assessment focused on the age, condition, and replacement/rehab cost of assets, and included projections for the remaining useful life and cost to maintain in a state of good repair for each asset, over various future time frames. The assessment used a fairly standard five point condition rating system (new, very good, good, fair, and poor). There were various adjustments made to the cost to take into account the true expense of replacement including soft costs and system disruptions.

The 2010 condition assessment is intended to provide direct input into the CIP and create a condition-based system for replacement/rehab of assets using a consistent set of prioritization tools and metrics. The database that results from the assessment is also expected to have a user interface that allows agency staff to produce reports and summaries of conditions as a basis for developing and prioritizing projects across different parts of the agency. The tool is also intended to allow for analyzing different "what-if" scenarios for investment strategies, to determine the impact on achieving state of good repair and maintenance objectives. The inventory is also intended to be aligned with funding and procurement information, so that project costs and schedules can be accurately analyzed.

Sweet, J. "Niagara Frontier Transportation Authority Overview." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation provides an overview of the Niagara Frontier Transportation Authority (NFTA) and its assets, and indicates that the condition of assets is currently maintained in the Ellipse maintenance management software. As required by the New York State DOT, NFTA's buses are given a 1–5 ranking every year, and NFTA was in the process of undertaking an FTA-funded facility condition assessment to support the development of a 5-year capital program.

Tuccillo, R. "Perspectives on Reauthorization." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation summarizes the state of SGR investment needs in the United States. For the entire industry, the yearly estimate for investment needed to attain and maintain a state of good repair is approximately $16 billion, while the current level of investment is approximately $9.3 billion. As with the results of the rail modernization study, current investments are not even keeping up with current SGR needs, meaning that the estimated $80 billion backlog of SGR needs is growing every year, with impacts on safety, performance, and customer satisfaction (and ultimately, ridership and other downstream outcomes). In addition to TERM, FTA also collects information about transit systems through the National Transit Database filings, as well as through information filed in TEAM (FTA's electronic grant management system) and through special studies and financial analyses that are performed periodically.

The presentation presents various options for better funding SGR, including the possible creation of a temporary SGR investment fund that would be targeted towards reducing the backlog of SGR needs. One issue with creating a dedicated funding source based on SGR needs is that it would penalize agencies that have done a good job of maintaining SGR and reward those that have done a poor job of maintenance and have a larger backlog. Other suggestions for financing include Grant Anticipation Notes, various forms of Infrastructure Banks (both state and federal), capital leasing, and the TIFIA program. The presentation also suggests that there are models for private sector investments and public-private partnerships that may help to alleviate some of these funding issues.

Valdes, V. "State of Good Repair Research." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation provides an overview of FTA's various research programs and indicates some potential ways in which SGR issues could be integrated into this existing research agenda.

Waaramaa, E. "State of Good Repair: MBTA Practices and Lessons Learned." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

This presentation provides a detailed description of the MBTA's approach to SGR. The presentation was updated in 2010 for the 2nd State of Good Repair, discussed subsequently in this review.

Waaramaa, E. and Jaffe, D.M. "FTA – Industry SGR Working Group." Presented at the 1st State of Good Repair Roundtable. FTA, 2009.

The presentation provides an overview of state of good repair issues, describes the purpose and goals of the roundtable and other joint industry efforts, and gives a definition of state of good repair. It describes a potential asset condition assessment approach considered by the SGR Working Group. The rating is a composite value that characterizes the condition of an asset on a scale from 1 (worst condition) to 5 (best condition). The rating incorporates subratings for asset age, asset condition, asset performance and level of maintenance.

Baker, S. "Transit Asset Management Training Program." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation provides a summary of an effort by the National Transit Institute (NTI) to develop a training module for asset management. At the time of the roundtable, the team had begun drafting the course and was hoping to begin course offerings by late August 2010, via www.ntionline.com. The course was designed for mid- to senior-level managers who have day-to-day responsibility for transit assets.

Cruz, R. "International Transit Studies: Tools and Systems." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation provides an overview of asset management techniques from different transit systems around Europe based on the results of TCRP's State of Good Repair International Study Mission. Many of these agencies are adopting PAS 55, a standard for whole life asset management developed in the United Kingdom. A whole life asset management approach encompasses decisions about which assets to acquire initially, how to use and maintain those assets, and how to recondition, replace, or dispose of those assets. This approach also takes into account the risk associated with an asset, not just its condition, to better determine the criticality of that asset. The presentation also distinguishes between measuring the condition of an asset and measuring the performance/output of that asset, which may result in different investment decisions.

Information about specific European cities is also summarized:

- London, UK, created a PPP to develop and implement an asset management and state of good repair program, with a goal of bringing the system back to a state of good repair within 22.5 years. There were three output-based contracts with a term of 30 years, tasked with asset management, bringing systems up to an overall good condition with an upgrade level of performance, and expanding capacity and integrating the network. However, this program has not been successful, with all contractors suffering financial difficulties, and two defaulting on their contracts, requiring a takeover by Transport for London.

- Nottingham, UK, is also creating a 30-year PPP for its tram system, with funding set aside for a mid-life rehabilitation of the rail vehicles. Nottingham is also implementing an asset management system for its highway and bus assets.
- Strasbourg, France, does a full inventory of assets by component, with condition assessments done on an irregular basis. They are also performing infrastructure assessments according to the PAS 55 standard.
- Karlsruhe, Germany, bases maintenance of track and rolling stock on inspections and driver feedback, without separate asset assessment. There is a currently a major backlog of SGR needs.
- Berlin, Germany, appears to take a more deterministic approach, with vehicles having a major rehabilitation planned after 8 years and bridges after 10 years. They are required to maintain a 10 year capital program and keep ongoing track of the maintenance backlog.
- Oslo, Norway: A full assessment of the system is conducted every three years, while a condition assessment of tracks is performed twice a year by a contractor. This information is then used for capital planning.

Ensor, J. "Innovative Financing Options for State of Good Repair Investments: Tools and Case Studies." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation reviews financing tools for transit investment, including:

- Tax Exempt Borrowing: The traditional method of generating revenue; must be repaid either from dedicated funding source or from general funds of agency (or financial backing agency).
- Build America Bonds: Taxable bonds, but U.S. Treasury subsidizes 35% of interest payments.
- TIFIA Loans: Provide loans with very attractive and flexible terms, for up to ⅓ the cost of a capital project.
- Grant Anticipation Notes: Borrowing secured by future formula grant funding.
- Qualified Energy Conservation Bonds: Transit is eligible, but has not used. Provides 0% interest borrowing for 15-year loans.
- Station Retail: Redevelopment and rehabilitation of stations can lead to the creation of additional retail opportunities that generate additional lease revenue that can fund the station improvements through advance bonding. This requires a healthy retail market.
- Historic Preservation Tax Credits: Can be used to leverage private financing from investors who can take advantage of tax credits.
- Tax Increment Financing: Uses anticipated increases in tax revenue resulting from increased land values to finance improvements that will generate those increases.
- In-Kind Private Sector Contributions: Can be voluntary based on perceived benefits and/or philanthropy, or required as part of development permitting process.
- Naming Rights: Can apply to stations, vehicles, or entire system.
- Energy Saving Investments: Can work with utilities to obtain initial financing for projects that will reduce long-term energy costs.
- Station-Specific Fare Surcharge: Additional charge for boarding at a specific station, to pay for maintenance and improvements dedicated to that station.
- Innovative Project Delivery: Models such as DBOM and Public-Private Partnership can be used to shift risk and expense associated with maintaining a state of good repair to the private sector. Requires well-written contracts, good inspection and oversight, and stable private sector partners. An analytical business case is required to decide on best approach to these models.

The presentation concludes that though the use of innovative financing techniques to support SGR needs has been limited, innovative financing may be attractive for addressing immediate needs, particularly in challenging revenue situations.

Garino, P. "New Jersey Transit State of Good Repair." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation describes New Jersey Transit's (NJT's) SGR efforts. NJT has spent the past 30 years developing a statewide transit network made up of previously separate (and generally private) railroad lines, bus systems, and a light rail line. The 1980s were focused on integrating these disparate elements, while the 1990s were focused on system improvements and expansions. In the past several years, NJT has taken a "back to basics" approach focused on ensuring a state of good repair and enhancing capacity. NJT's approach to SGR starts with prioritization through the various funding sources and the capital investment strategy, and then proceeds to management tools for ongoing project prioritization and project management.

NJT recently transitioned from a yearly project prioritization process to an ongoing, real-time process that is designed to be flexible and interdisciplinary. NJT's internal project prioritization process is based on a multiyear time frame with constrained future years, and attempts to push decision making down to the level of those closest to the infrastructure conditions. Project prioritization criteria are customized by mode, type of asset, and type of project, so that the criteria accurately reflect the characteristics of those needs. Funding for transit infrastructure had been increasing in New Jersey, particularly as a share of overall transportation investment, and NJT tends to spend approximately ⅔ of its capital program on SGR activities. Since its creation, NJT has invested heavily in rehabilitation and replacement of assets, and now considers its entire system to be in a state of good repair. One of the key lessons learned by NJT is that project prioritization needs to take into account the geographic, scope, and other linkages between projects.

Gates, K. "TERM Lite: Building Better Technology for the Industry's Use." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

TERM Lite (Local Investment Tool Edition) is a variation of the Transit Economic Requirements Model (described in other sections of this literature review) that can be used for long-range capital planning by individual agencies, that is available free from FTA's web site. Using the same structure as TERM, it focused on the needs of a single agency and can be used to produce estimates of funding needs and asset conditions under different funding and asset scenarios. The presentation provides a number of examples of the funding and asset condition analyses that can be done using TERM Lite, which is similar to the types of analyses that are presented in other descriptions of TERM. These include determining the SGR backlog and normal replacement needs, projecting the future condition of assets based on investment scenarios, and determining yearly funding needs over a 20-year time frame. The key point of this presentation is that FTA has made TERM Lite available for individual transit agencies to use in their asset management and capital programming activities, in addition to the overall version of TERM that is used at a national level.

Hiott, J. "Training for Asset Management." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation provides a basic definition of asset management, which overlaps with information discussed in greater detail in other presentations. It then discusses the importance of training for personnel, both in terms of asset management principles and practice and in terms of performing maintenance. For asset management itself, training is available through the National Transit Institute, through various conferences and workshops, and via industry events such as these roundtables. The APTA Standards program is another potential training and education resource. Four types of documents can be created through the Standards Program: true standards, recommended practices, guidelines, or white papers. This would provide the industry with an opportunity to create, approve, and disseminate information on topics relating to asset management. The presentation also highlights the importance of developing and maintaining a Fleet Management Plan for rolling stock, as well as a Facilities Management Plan for fixed assets. Another suggestion is to work with manufacturers closely on developing training and asset management programs for their equipment.

Hubbell, M. "State of Good Repair Assessment–Dallas Area Rapid Transit." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

DART has expanded its rail system rapidly over the past 15 years, but has also experienced flat or declining revenue, particularly from sales taxes. However, the agency board's financial planning parameters include the maintenance of a reserve fund for asset maintenance and rehabilitation, and the size of this reserve fund is based on an asset condition assessment, which is performed every 5 years. The goal of this assessment is to gain a high level of understanding of asset conditions, which is done through a sampling of asset conditions, not a complete inventory and inspection of all assets. This represents a statistical approach that considers the overall condition of logical groups of assets, as opposed to a complete enumeration of the condition of every asset, which can be an overwhelming undertaking for some agencies. DART also focused the condition assessment on assets that are key for safety or system operations, which are most critical for safe operations.

The assessment evaluates whether asset conditions are deteriorating at the expected rate, and compares maintenance and financial plans to the results of the condition assessment. Assets are divided into eight overall categories reflecting the major classes of assets, and inspections are performed by an in-house team. The level of sampling varies from 15% to 100%, with the full asset inspection being done for HOV facilities and right-of-way systems. DART's assets are ranked on a five point scale, with 5 being the best and 1 indicating that the asset is non-functional and requires major repair (such as a bus damaged in an accident). Based on these inspections, DART determined that most of its assets are at their expected condition, although a limited set of components were identified as requiring special attention for maintenance or replacement.

James, A. "Addressing the Challenge: Formulating a Definition of SGR for a Federal Program." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation discusses alternative definitions of SGR for potential use in a new federal program. The presentation proposes three possible definitions of SGR:

Model 1:

A transit system is in a state of good repair when the following criteria are met:

- Possesses and maintains a comprehensive list of its capital assets and rolling stock;
- Possesses an asset management plan which is integrated into the management processes and practices of the agency; and
- A set percentage of its assets are within their articulated useful life and remaining assets are performing at their designed for function.

Model 2:

A transit system is in a state of good repair when:

- System components are properly maintained or replaced, in accordance with:
  - The owner's approved O&M procedures and schedules, or
  - The OEM's recommended criteria when owner's procedures do not exist, or
  - Industry standards when (a) or (b) are not available, and
- Satisfactorily performs intended design function

Model 3:

A transit system is considered to be in a state of good repair if it exhibits the following characteristics:

- Safety: Transit infrastructure and vehicles are well-maintained and replaced before their condition deteriorates to the point of presenting a safety risk; and
- Quality Transit: Infrastructure and vehicles meet customer expectations for comfort and reliability.

While there is no recommendation for which definition should be used, it is clear that a standard definition will need to be accepted in order to move forward with a federal funding program.

James, A. "Asset Management Pilots: MPOs and Transit Agencies." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation discusses language in the FY2010 Senate Appropriations bill that would direct FTA to take a leadership role in the development and improvement of asset management systems within the transit industry, including setting up pilot programs and developing standards. In implementing a pilot program, FTA would be looking to work with transit agencies of differing sizes, with state DOTs, and with MPOs, to support the development and implementation of innovative transit asset management systems and associated SGR investments. They would also be looking for planning phase projects that show how asset management can be used by MPOs and other agencies to support planning needs and processes. The results of these pilot programs would then be used to support the further implementation of asset management systems and standards, presumably in support of an SGR funding program at the federal level.

Matichich, M. "Asset Management in the Water/Wastewater Industries: A Case Study from the Upper Occoquan Service Authority (UOSA) in Centreville, VA." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

Over the past ten years, the water and wastewater industries have sponsored a number of documents related to improved asset management, including a guide to implementing asset management in the industry. This presentation summarizes definitions and approaches to risk assessment commonly used in the water/wastewater industry. A common approach is to use a "top down" approach that analyzes risks at a facility level and then identifies steps necessary to mitigate those risks and prioritize investment projects. This differs somewhat from an approach that starts by cataloging each asset and assessing its condition, and building up the asset management approach from the bottom up. This top down approach allows for the prioritization of both asset condition assessments and investment projects based on the risk associated with the failure of those components. In the example provided from the Upper Occoquan Service Authority, a top down approach was used to identify 1,912 assets that merited detailed field assessments, based on the risk associated with each component. Factors specific to this agency were used to determine the severity of component failure and the likelihood of component failure, to determine the risk associated with each asset. This approach obviously requires good data about and good experience with the assets in question, but can reduce the need for evaluation of assets that do not represent a great risk. The approach was used to produce an overall condition ranking of the assets, and a detailed risk condition ranking for each key asset. The risk assessment information can be tied to capital costs for investments to help prioritize capital investments and obtain the best "bang for the buck."

McMillan, T. "State of Good Repair: Potential Concepts." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation discusses the potential creation of an SGR program to fund improvement activities aimed at eliminating an SGR backlog or avoiding the creation of one. This presentation covers some of the key concepts that FTA is looking at, including defining SGR, what would be included in an SGR funding program, and some of the key technical and administrative issues. FTA sees SGR as important both to protect past federal investments and to ensure safe and reliable public transit, particularly for communities that are transit dependent. Maintaining a state of good repair for all key transportation modes is also a goal in U.S. DOT's strategic plan. This is particularly an issue for FTA given the large backlog of SGR needs and an investment level that is not keeping up with ongoing needs.

The key first step in attaining a state of good repair is having an asset management program, and FTA is likely to require such a program or system, along with an asset management strategy, as a prerequisite for receiving funding under any SGR program. The U.S. Senate is also discussing requiring asset management as part of transit safety legislation. An FTA SGR program would be aimed at eliminating existing backlogs, as well as preventing the creation of new backlogs through strategic investments, and would fund projects identified through an asset management system. The complexity of the asset management system and the reporting required by FTA would likely be based on the size and complexity of each system (or classes of systems), and FTA is cognizant of the danger of simply rewarding systems that have done a poor job of asset management and SGR maintenance, and therefore have a large backlog that is eligible for funding.

Nutakor, C. "Current Asset Management Practices: A National and International Review." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation summarizes the results of the FTA report *Transit Asset Management Practices: A National and International Review* described previously.

Rodriguez, R. "Chicago Transit Authority Overview." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

Most of this presentation is a review of the history and operations of the CTA, but it also discusses the SGR backlog for CTA, including the fact that 38% of stations, 22% of tracks, 45% of substations, 37% of bus garages, and 32% of rail cars are in service past the end of their useful life. Overall, CTA estimates an unfunded need of $6.8 billion in SGR needs over the next five years. The presentation also discusses past and future plans for rehabilitation and replacement, including the difficulty in balancing those needs against system expansion needs, as well as the need for public outreach and environmental approvals associated even with rehabilitation projects.

Rokos, C. "Chapel Hill Transit: SGR Asset Management Capital Program." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

Chapel Hill Transit is in the process of developing a capital program that is based on an asset management approach and their responsibility to maintain, repair, and replace capital assets and facilities, particularly those that integrate with other departments of the Town of Chapel Hill. Asset management is an important part of developing both the short- and long-range CIPs, taking into account the system's long-term needs. A good asset inventory, along with regularly updated condition assessments, are crucial inputs into the CIP, particularly for prioritizing investments given limited/insufficient funding. Other factors that impact the CIP include safety, regulatory compliance, and sustainability. Because it is a relatively small agency, Chapel Hill Transit is challenged to implement and maintain a good asset inventory and condition assessment, while performing all of the other necessary functions. Training for employees is also a challenge, and Chapel Hill Transit is looking to FTA and larger agencies for advice and guidance on asset management and maintaining a state of good repair.

Rutledge, J. "International Transit Studies: State of Good Repair Definition and Measurement." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation summarizes findings from TCRP's State of Good Repair International Study Mission. While the concept of state of good repair is readily understood in Europe, there was no consistent definition across transit agencies, and few agencies had a specific definition. Of the agencies visited, LU appears to have the best information on state of good repair, possibly as a result of the need to clearly define performance and asset management as part of various public-private partnerships. LU replaces buses on a 3-year cycle, while other assets are rehabilitated or replaced based on inspections or on an as-needed basis. For LU, "An asset that meets an established set of condition requirements and risk requirements and has at least 1 year of life remaining is considered in a state of good repair." It is important to note the inclusion of risk requirements in this definition, since London rates both the condition of the asset (in terms of remaining service life) and the risk associated with the failure of that asset.

Most European agencies replace buses every 12–15 years, and rail rolling stock within 30 years, with a typical mid-life overhaul/rehabilitation. For fixed assets, repairs and replacement are typically performed based on a cost-benefit analysis, with condition assessments and cost-benefit analyses performed based on the life cycle of the asset in question. Berlin, Germany, and Oslo, Norway, are systems that are both very focused on state of good repair and good asset management, including having established life cycles for assets, performing condition assessments, and developing prioritized capital plans to address SGR needs. Most European systems are committed to providing a high quality experience that can attract choice transit riders, and appear to see good asset management as a key element of that commitment.

Smith, F. "Asset Management Process and Strategy." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation summarizes NYCT's asset management process. The MTA (and therefore NYCT) maintains two key capital prioritization tools; the 20-year needs assessment that provides a high level analysis of long-term needs, and the ongoing 5-year capital programs, which lay out a more detailed set of project priorities in 5-year increments (although the integrity of the 5-year capital program has been somewhat reduced recently due to insufficient funding). Asset inventories are key to producing both documents, particularly for the longer-term needs assessment, which is not strictly constrained by funding availability. For the 20-year needs assessment, which is updated every five years, individual departments within NYCT are responsible for updating both asset inventory and the condition assessments, typically based on more detailed maintenance databases. Groups responsible for types of components are then responsible for recommending the investment strategy and the pace of investment, along with a justification for those recommendations. This then leads to a set of projects grouped into 5-year increments, which are then transitioned into the 5-year capital program that is the vehicle for project delivery.

This project prioritization process is supported by a varied set of computer tools, most of which are based on databases or spreadsheets developed in house. The Project Status Reporting (PSR) system tracks project budgets and milestones and also adds information about asset conditions, as well as provides public outputs including the public "dashboard" available on the MTA web site. This also provides a vehicle for tracking needs and projects in the 20-year needs assessment.

The presentation also provides examples of asset management inventories for four different types of assets:

- Tracks and switches, which use a detailed database organized by track segment, including both short-term maintenance and long-term rehabilitation needs. Prioritization is also driven by track access opportunities, given the difficulty of general outages.
- Traction power, which uses a spreadsheet broken down according to the different elements of the traction power system, including the different components of each substation.
- Rail cars, which are programmed for a 40-year replacement, but may be used longer or replaced earlier depending on asset condition data. Although detailed car-level maintenance records are available, investment decisions are made at a fleet level, not based on individual car conditions.
- Stations, which recently switched from a full rehabilitation/modernization approach to a component rehabilitation model based on individual asset condition data.

NYCT's experience has been that good asset management creates greater credibility with funding partners, since there is greater stability/predictability and fewer surprises in the capital programming process. Consistent reporting and tracking over time is also critical, so that changes over time can be explained by investment, or lack thereof.

Tepke, G. "Funding & Finance for State of Good Repair in European Transit Systems." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation summarizes findings from TCRP's State of Good Repair International Study Mission. Funding for SGR is a challenge in all locations, despite the European reputation for better investment in transit. There have also been attempts at privatization of service operations, including asset management, with mixed results, particularly for the Infracos on the London Underground. Many of the relatively recent major transit investments, particularly for the construction of light rail/tram systems, are reaching the midway point of their expected useful life, which is beginning to raise questions about SGR needs and funding. As in the United States, the funding sources for these investments are varied and depend in part on political considerations, particularly given current European austerity programs.

Waaramaa, E. "Asset Management Systems: MBTA Approach and Lessons Learned." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation provides a detailed description of the MBTA's approach to SGR, with a particular emphasis on their SGR database. MBTA defines SGR as "condition where all assets perform their assigned functions without limitation." The MBTA's SGR database takes in information about asset condition, but also considers the operational impact of performing or not performing maintenance, in an attempt to prioritize not only based on asset condition, but also based on that operational impact. This information is then translated into a score associated with the maintenance required for that asset, which can be used in setting investment priorities. The system can be used in developing SGR backlog estimates, as well as for playing out varying investment scenarios and seeing the resulting backlog. This information can also be used to develop popular and political support for increased investment. SGR needs are particularly important to older systems such as the MBTA, particularly as they have seen significant ridership increases in recent years, reversing what had been an overall declining trend. In 2006, the MBTA estimated its SGR backlog at $2.7 billion.

The presentation makes clear that this SGR analysis is not the only basis for making investment decisions, since other factors such as safety and legal mandates (i.e., ADA) must also be given consideration, in part based on the goals outlined in the MBTA's enabling legislation. At the time of this presentation, the MBTA was working on developing an add-on module to their database that would analyze the impact of different capital replacement decisions on the operating budget. The presentation highlights the need for management and staff support and the need for quality data that is available in a timely fashion.

Williams, T. "Research Activities to Support the State of Good Repair." Presented at the 2nd State of Good Repair Roundtable. FTA, 2010.

This presentation summarizes ongoing research activities that support state of good repair activities—including this research project. Two studies have recently been completed, one that created a condition-based maintenance evaluation model to track railcar maintenance and another that assessed the applicability of the Six Sigma quality approach to heavy railcar maintenance. In addition, the following research activities are proposed:

- Best practices research on assessing asset conditions, with the goal of improving the condition of safety-critical assets.
- Additional research on improved methodologies, such as Six Sigma and others.
- Improved documentation of the characteristics of railcar assets, to identify maintenance improvements that can increase safety and fleet availability.
- Best practices for dealing with severe/extreme weather conditions, to improve safety and operations during those conditions.
- Analysis of the cost and benefits of implementing platform door systems on existing and new systems.
- Asset management pilots (as described earlier) that focus on differing size agencies, as well as improving the planning process.

B.4 Other References

Stivers, M.L., Smith, K.L. Hoerner, T.E. and Romine, A.R. *NCHRP Report 422: Maintenance Quality Assurance Program Implementation Manual.* TRB, National Research Council, Washington, D.C., 1999.

This manual contains guidance for highway agencies in the development and application of a maintenance quality assurance (MQA) program. The manual outlines a prototypical MQA program, which includes definition of maintenance levels of service for characterizing maintenance quality, sampling of conditions, and prediction of budget requirements to achieve a target LOS. The manual provides step-by-step procedures for establishing a MQA program, and profiles the MQA programs in four agencies. In the examples presented in the manual, maintenance LOS are typically defined for maintenance of pavement, as well as for roadside assets such as the right-of-way, fences, shoulders, drainage features and traffic safety features. LOSs are frequently represented using a score that combines inspections of a number of different features or characteristics and/or on an A–F letter scale.

Evdorides, H.T., Kerali, H.G.R., Reviere, N. and Ornskov, J.K. "Condition Based Method for Programming Road Infrastructure Maintenance." In *Transportation Research Record: Transportation Research Board, No. 1816.* Transportation Research Board of the National Academies, Washington, D.C., 2002.

This paper provides an overview of the Road Infrastructure Maintenance Evaluation Study (RIMES) project of the Road Transport Programme of the Commission of the European Union, which aims to integrate pavement and bridge management systems. It describes how pavement and bridge projects follow a similar pattern for programming, where their field condition data are collected then assessed using engineering criteria, assets below certain threshold levels are considered for treatment, and projects are prioritized based upon engineering and economic analyses and programmed based upon available funding. It proposes that road maintenance projects can include both pavement and bridge components to achieve lower user and construction costs through an annualized cost method, which enables comparison of assets with different life cycles.

Berechman, J., and Paaswell, R. "Evaluation, Prioritization and Selection of Transportation Investment Projects in New York City." In *Transportation* Vol. 32, no. 3, p. 223–224. Springer, 2005.

This paper describes a method to evaluate high capital cost transportation projects for New York City and the application of this method to rank and prioritize eight projects at early stages of planning. The authors describe the selection of a subset of projects from a large pool and the identification and measurement of the benefits and costs of projects on the transportation network and the economy. Net present value equations can relate capital costs, debt service and maintenance and operating costs to changes in ridership, travel times, levels of commercial, residential and retail development, job levels, incomes and tax flows. The authors propose a goal achievement matrix framework to summarize the measures and their relative importance and to rank projects according to their cost-benefit performance.

Lambert, J., Peterson, K., Wadie, M., and Farrington, W. *Development of a Methodology to Coordinate and Prioritize Multimodal Investment Networks.* Virginia Transportation Research Council, 2005.

This report describes an analytical approach proposed for Virginia DOT to coordinate and prioritize multimodal investment network (MIN) projects, which are large scale projects considered in Virginia's long range plan, VTrans2025. It proposes performance measures for six classes of performance criteria, a scoring methodology relative to these measures, and 5 different policies to assign weights to the performance measures. The projects can be compared to each other based upon their averages and ranges of scores according to the weighting policies. The report describes how VDOT can use the resulting scores to prioritize low cost investment alternatives that meet performance objectives.

Gharaibeh, N.G., Chiu, Y.C., and Gurian, P.L. "Decision Methodology for Allocating Funds Across Transportation Infrastructure Assets." In *Journal of Infrastructure Systems,* Vol. 12, No. 1, pp. 1–9. ASCE, 2006.

This paper proposes that decision makers use multi-attribute utility (MAU) methodology to allocate available funds across infrastructure classes or programs. The methodology involves establishing a relationship between funds expended on each asset class and its overall performance and developing a utility function for each asset class that reflects the decision maker's attitude toward the risk of failure or poor performance for that asset. The utility functions combine into a MAU function for all asset classes to create an allocation scenario. The decision maker can select the allocation alternative with the highest expected MAU. The MAU approach can translate values such as safety and comfort to prioritize infrastructure investments that maximize performance.

Grussing, M.N., Uzarski, D.R., and Marrano, L.R. "Optimizing Facility Component Maintenance, Repair, and Restoration Investment Strategies Using Financial ROI Metrics and Consequence Analysis." In *Applications of Advanced Technology in Transportation: Proceedings of the 9th International Conference.* ASCE, 2006.

This article presents a business process framework for the proactive management of facility assets. Building infrastructure conditions should be assessed at a level that allows predictions of future conditions and preventive maintenance while not creating prohibitive expenses for inspections. Standardized metrics, such as condition index (CI), can provide consistent, objective measures of the physical condition of assets and establish a means to compare all building components. Since not all components need to be maintained at the same level, organizational goals and accepted risks would identify which components should be kept at higher conditions. A curvilinear model that relates repair costs as a function of CI can help determine when corrective actions should be explored. Alternatives include "Run to Failure," "Stop Gap Repair," "Major Corrective Repair," and "Replacement/Capital Renewal." Investment strategies should minimize life cycle ownership costs, maximize facility performance, and manage risk.

Perrin, J. and Dwivedi, R. "Need for Culvert Asset Management." In *Transportation Research Record 1597.* TRB, National Research Council, Washington, D.C., 2006.

This paper discusses the importance of inventorying underground culvert infrastructure as a critical component of highway asset management. Neglecting culverts can result in sinkholes, expensive failures that impact safety and user-convenience. A survey of U.S. state departments of transportation (DOT) shows that only a few are working toward developing an inventory database and planning to implement an inspection program. The paper describes the example of the New York State DOT Culvert Inventory and Inspection System (CIIS) database to determine which culverts need close monitoring and to prioritize culvert replacement.

Maji, A. and Jha, M.K. "Modeling Highway Infrastructure Maintenance Schedules with Budget Constraints." In *Transportation Research Record 1991.* Transportation Research Board of the National Academies, Washington, D.C., 2007.

This article develops a mathematical model to determine optimal maintenance schedules over a specified period of time. It presents an objective function to minimize the total maintenance cost in the design period subject to constraints on the condition level and budget. It proposes an algorithm to solve the function and applies it to a numerical example that covers 11 different elements across three different asset classes (lighting, guardrail and signs) to produce an optimum maintenance schedule over a time horizon of five years.

Markow, M.J. *NCHRP Synthesis 371: Managing Selected Transportation Assets: Signals, Lighting, Signs, Pavement Marking, Culverts, and Sidewalks.* Transportation Research Board of the National Academies, Washington, D.C., 2007.

This report presents the state of practice for managing transportation infrastructure assets other than pavements and bridges, identifies potential improvements, and identifies areas for further research. The study focuses on traffic signals, lighting, signs, pavement lane striping and other markings, drainage culverts and pipes (but not bridges), and sidewalks. While technical guidance on asset construction or installation exists across all assets, a lack of a complete, accurate, and current inventory of these selected assets was viewed by many agencies as a key issue to address. Budgeting relies to some degree on asset inventory, condition, or level of service, but performance-based factors are not the primary drivers. New technologies and a dynamic commercial environment may provide many benefits but may also complicate an agency's ability to remain current regarding the performance and compatibility of new versus existing products. The report provides a comprehensive review of the asset management literature pertaining to each of the asset groups reviewed, including approaches for prioritizing investments. Further, the report details the results of a national survey of state DOT pertaining to their approaches for managing the selected assets.

Morcous, G. "Pareto Analysis for Multicriteria Optimization of Bridge Preservation Decisions." In *Transportation Research Record 1991.* Transportation Research Board of the National Academies, Washington, D.C., 2007.

This paper describes an approach to making bridge preservation trade-off decisions with the goal of achieving a Pareto optimal solution, and demonstrates the application of this approach on bridges in the Nebraska Bridge Management System. The paper illustrates the approach by developing a solution for a trade-off decision between maximizing the life-cycle cost and maximizing the condition of decks for a network of bridges in Nebraska. It adopts Markov stochastic chains that relate costs to probabilities that a bridge deck would change condition levels and maintenance alternatives. A genetic algorithm is used to produce solution curves for a set of maintenance activities, from which the decision maker can select an option.

Patidar, V., Labi, S., Sinha, K.C., and Thompson, P. *NCHRP Report 590: Multiple-Objective Optimization for Bridge Management Systems.* Transportation Research Board of the National Academies, Washington, D.C., 2007.

This report describes an approach for optimizing investments in highway bridges including the following objectives: agency and user cost minimization, preservation of bridge condition, traffic safety enhancement, and protection from extreme events. The report details the development of a utility function incorporating these objectives, and describes the Multiple Objective Optimization System (MOOS) which uses the utility function in conjunction with data from the AASHTO Pontis Bridge Management System (BMS) to perform a multi-objective optimization. The report includes a comprehensive review of bridge management systems, models and prioritization approaches, as well as literature related to multi-objective optimization for transportation investments.

Cambridge Systematics, Inc., Applied Research Associates, Inc., Arora and Associates, KLS Engineering, PB Consult, Inc., and Lambert, L. *NCHRP Report 632: An Asset-Management Framework for the Interstate Highway System.* Transportation Research Board of the National Academies, Washington, D.C., 2009.

This report develops a practical framework for applying asset-management principles and practices to manage Interstate Highway System (IHS) investments. It recommends that each IHS owner develop an Interstate Asset Management Plan detailing current conditions and performance, predicted future conditions, and investment strategy and risk assessment for IHS assets. The report provides a review of performance measures, asset data, systems and tools for managing highway assets, and describes the pilot application of the recommended IHS asset management framework to three interstate corridors.

Cambridge Systematics, Inc. and Little, P. *Post-Audit of Wayside Detector Costs and Benefits.* Technical report prepared for the Association of American Railroads (AAR) Transportation Technology Center, Inc. AAR, 2009.

This report details an audit of the costs and benefits to the U.S. rail industry of implementing wayside detectors to identify rail car defects. The report describes the implementation of detectors on U.S. railroads, including Wheel Impact Load Detectors (WILD), Overload & Imbalanced Load Detectors (OILD), Acoustic Bearing Detectors (ABD), Warm Bearing Trending (WBT), Hot Wheel Detectors (HWD), Cold Wheel Detectors (CWD), Truck Hunting Detectors (THD), Truck Performance Detectors (TPD), and Wheel Profile Measurement (WPM). The report summarizes the results of interviews of staff at five Class I railroads to assess how the railroads utilize data from these detectors, and the costs and benefits incurred in their use.

Guerre, J. and Evan, J. Applying System-Level Performance Measures and Targets in the Detroit, Michigan, Metropolitan Planning Process. In *Transportation Research Record 2119.* Transportation Research Board of the National Academies, Washington, D.C., 2009.

This paper describes an effort by the Southeast Michigan Council of Governments (SEMCOG) to prioritize transportation investments using the AssetManager NT tool described previously. SEMCOG used AssetManager NT to show predicted performance at different budget levels for investments in pavements, bridges, highway capacity, safety, transit and non-motorized projects. For pavements and bridges SEMCOG used models provided by Michigan DOT to predict performance at different investment levels. SEMCOG used the FHWA Highway Economic Requirements System (HERS) to predict mobility impacts, and used spreadsheet models for other investment areas. For transit investments SEMCOG's measure of effectiveness was system extent relative to the current transit system.

Louch, H, Robert, W, Gurenich, D. and Hoffman, J. Asset Management Implementation Strategy. Report NJ-2009-005 prepared for the New Jersey Department of Transportation (NJDOT). NJDOT, 2009.

This report describes a research effort performed for NJDOT to develop an asset management decision support model. The report reviews asset management practices at NJDOT, and compares these to best practices at other DOTs. It then formulates a multi-objective optimization model for supporting project prioritization for pavement, bridge, safety and mobility investments. Also, the report describes the development, through a workshop with NJDOT staff, of a utility function for use with the model.

Mrawiral, D. and Amador, L. "Cross-Assets Trade-off Analysis: Why Are We Still Talking About It?" Presented at the 88th Annual Meeting of the Transportation Research Board. Transportation Research Board of the National Academies, Washington, D.C., 2009.

This paper details a cross-asset optimization model called TAMWORTH implemented for the New Brunswick Department of Transportation (NBDOT). TAMWORTH is an implementation of an optimization model developed by Remsoft Inc. and used for optimizing investments in forestry. NBDOT adapted the model to optimize investments in rehabilitation and replacement of pavement and bridge assets over time. Their effort was motivated by the recognition that there existed at the time no other production system for performing comprehensive global optimization and trade-off across multiple asset types. TAMWORTH formulates a long-term planning optimization problem as a standard linear programming (LP) problem with the objective of minimizing costs given a set of condition targets, or maximizing condition given a budget, subject to constraints. The paper presents results obtained for five different scenarios with different objective functions and constraints.

Dehghanisanij, M., Flintsch, G.W., and Medina-Flintsch, A. "A Flexible Framework for Sustainable Multi-Objective Cross-Asset Infrastructure Management." Presented at the 89th Annual Meeting of the Transportation Research Board. Transportation Research Board of the National Academies, Washington, D.C., 2010.

This paper discusses an ongoing research effort to develop a framework for optimizing cross-asset resource allocation decisions. It presents a conceptual framework for cross-asset optimization, discusses the use of performance measures and considerations in selecting performance measures, and summarizes a review of the literature pertaining to cross-asset resource allocation.

FHWA. *Beyond the Short Term: Transportation Asset Management for Long-Term Sustainability, Accountability and Performance.* Publication FHWA-IF-10-009. FHWA, 2010.

This provides guidance for implementing an asset management approach in a DOT, and relates implementing asset management to agency efforts to achieve long-term sustainability of their infrastructure, demonstrate accountability, and enhance system performance. It provides case studies describing asset management implementation efforts at the highway departments in: North Carolina; Utah; Florida; Missouri; Maryland; New Zealand; Sweden; Queensland, Australia; and New South Wales, Australia. The case studies illustrate how asset management helps to drive change, set direction, and improve quality and to examine the structures, strategies, and information needed for successful implementation in a variety of settings.

Spy Pond Partners and Martland, C. *Post Audit of Association of American Railroads Rail Life Research.* Technical report prepared for the AAR TTCI. AAR, 2010.

This report details an audit of the costs and benefits to the U.S. rail industry of improvements in rail life resulting from AAR rail research, including improved metallurgy, maintenance practices, rail inspection and other improvements. The report summarizes the results of interviews of staff at six Class I railroads concerning the railroads' experience in replacement of rail, trends in rail life over time, impact of changes in metallurgy, maintenance practices, rail inspection, and other areas, and the degree to which recent improvements in rail life can be attributed to AAR research.

Spy Pond Partners and Stone, D. *Post Audit of Association of American Railroads Wheel Research.* Technical report prepared for the AAR TTCI. AAR, 2011.

This report details an audit of the costs and benefits to the U.S. rail industry of improvements in wheel life and defect rates resulting from AAR wheel and wheel-related research, including improved metallurgy, maintenance practices, railcar truck designs and other improvements. The report summarizes the results of interviews of staff at five Class I railroads concerning the railroads' experience in replacement of wheels, trends in wheel life over time, impact of changes in standards and technology, and the degree to which recent improvements in wheel life can be attributed to AAR research.

APPENDIX C

Interview Guide

Overview

You have been contacted as part of Transit Cooperative Research Program (TCRP) Project E-09: Prioritizing the Rehabilitation and Replacement of Existing Capital Assets and Evaluating the Implications for Transit. The project will address a key set of research needs required to help transit agencies improve their analysis of state-of-good-repair needs. The objectives of the project are to: develop a framework for public transportation organizations to use to prioritize rehabilitation and replacement of existing capital assets; and identify methods for assessing the positive and negative consequences of varying investment levels on key indicators of public transportation service and performance.

As part of our work on this project, Spy Pond Partners (SPP) is performing a review of the literature related to rehabilitation and replacement of capital assets, and contacting selected organizations to highlight insights and any notable aspects of their practices in this area. The following pages describe the topics we would like to address through a telephone interview with you. We would hope to cover these topics in a 1-hour conference call, with any additional follow-up questions detailing specific issues handled via email. We appreciate your participation in the interview process. For more information on the research, please contact:

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General

1. Name
2. Organization
3. Position
4. Overview of responsibilities

Establishing State-of-Good Repair Needs

1. Does your organization have a working definition for what constitutes a state of good repair?
2. How does your organization determine needs for rehabilitation and replacement investments?
3. How would you characterize the current state of repair of your organization's assets? To what extent do conditions vary by type of asset?
4. What trends have you observed regarding state-of-good-repair needs?
5. Does your organization have a process that ensures that all stakeholders are fairly and appropriately represented when determining state-of-good-repair investment needs?

Prioritizing State-of-Good Repair Investments

1. What methods does the organization use for prioritizing its investments?
2. Are any analyses performed to characterize the impacts of different investment levels? Alternatively, are there illustrative examples or case studies that have been used to make the case for state-of-good-repair investments?
3. Are factors such as life cycle cost of asset maintenance, alternative fuels, sustainability, social justice, and technological innovations incorporated in the process, and if so how?
4. In the event that available funds are not sufficient for addressing asset rehabilitation and replacement needs, what approaches are used to make trade-offs between different types of assets or investments?
5. To what extent is the prioritization process shaped by legal mandates or other constraints?

Measuring Performance

1. Does the organization have a program for reporting and monitoring performance? If so, describe.
2. What measures are used for characterizing asset conditions?
3. How is information on asset performance used to support analysis of investment needs?
4. Are specific performance measures used to support the prioritization process and/or communicate results? Which measures are used?
5. What approaches are used to communicate performance (e.g., dashboards, reports, etc . . .)? Which stakeholders receive communication on asset performance?

Systems and Data

1. What data are required to support the organization's prioritization and/or performance measurement approaches?
2. How frequently are required data collected, and at what resolution? What means are used to collect the data?
3. What computer systems are used to manage asset inventory and condition data? Are these customized or commercial-off-the-shelf (COTS) systems?
4. What computer systems are used to support the investment prioritization process? Are these customized or COTS systems?
5. To what extent are different systems used for asset management and project planning integrated, including systems for maintenance management, project planning, and financial accounting, and other related systems.

Other Issues

1. Who are the stakeholders in the organization's decision making?
2. How does the organization communicate to its stakeholders? How are stakeholder interests incorporated in the decision-making process?
3. Please describe any public private partnerships that may impact how the agency manages its asset inventory and/or prioritize investment decisions, and the role of any private sector partners.
4. What benefits has the organization realized as a result of its practices related to achieving a state of good repair? Has the organization realized improvements in performance, safety, reliability, productivity, its relationship with its stakeholders, or other benefits?
5. What are the major gaps in the organization's existing systems and processes for supporting capital asset investments?
6. Please describe any initiatives underway to improve the organizations' asset management-related systems and processes?
7. What are the greatest challenges in terms of improving the process for prioritizing asset rehabilitation and replacement investments?
8. Please describe any other issues or relevant factors you feel we should consider in performing the TCRP Project E-09 research.

APPENDIX D

Existing Practice Profiles

D.1 Amtrak Track Infrastructure Condition Assessment

Short Description: To improve its information on its assets, Amtrak has established a comprehensive condition assessment program, including periodic measurements made using track geometry cars, use of ground penetrating radar (GPR) for characterizing subgrade conditions, and use of light detection and ranging (LIDAR) for characterizing condition of drainage ditches. Also, Amtrak is working in conjunction with the FRA to implement ultrasonic detection for inspecting concrete ties.

Long Description: Amtrak is a federally owned corporation that provides passenger rail service nationwide. Amtrak owns a total of approximately 764 route miles, including the tracks for the Northeast Corridor, Pennsylvania and Keystone, Empire Corridor, and New Haven–Springfield services. Amtrak defines state of good repair as "a condition in which the existing physical assets, both individually and as a system are functioning as designed within their useful lives and are sustained through regular maintenance and replacement programs." Amtrak relies on a variety of techniques for assessing the condition of its track infrastructure, including visual inspections and non-destructive evaluation (NDE) techniques. Track walks are performed on a daily basis and used to detect a variety of issues requiring immediate attention, such as cracked ties. Concrete ties have been an area of particular concern on the Northeast Corridor. Tie condition is assessed in three categories depending on degree of severity. Also, Amtrak uses track geometry cars (twice weekly on the Northeast Corridor mainline, quarterly on other lines) to assess track conditions and geometry. To measure subgrade conditions, a geotechnical team runs ballast through sieves of various sizes. This approach is time consuming, and cannot be used to measure subgrade directly underneath ties. Thus, Amtrak is working to correlate sieve passing rates to GPR readings. GPR readings can efficiently detect areas of water pockets and drainage problems and be used to determine when the subgrade needs to be rebalanced. To identify where drainage ditches may be plugged every three to four years Amtrak scans the cross sections of its rails with light detection and ranging (LIDAR). Further, Amtrak is working with the FRA to use ultrasonic impact echo technology to better characterize tie conditions. In addition to these techniques, Amtrak uses data from onboard accelerometers on Amtrak's Acela fleet to identify areas along the corridor where ride quality has deteriorated. Though it can be difficult to decouple effects of special track work and car-specific conditions in this data, Amtrak has used this data to identify "long wave" resonance conditions that are difficult to detect using visual inspections.

D.2 LBT Maintenance Policies & Procedures Manual

Short Description: Long Beach Transit uses its Maintenance Department Policies & Procedures Manual to establish consistent practices for administration, inspections, planned, preventive maintenance activities, and unplanned repairs.

Long Description: Formed in 1963 as a municipal transit system and owned by the City of Long Beach, Long Beach Transit (LBT) serves the City of Long Beach, Lakewood, Signal Hill, Seal Beach, and other surrounding communities. To maintain its assets in a state-of-good-repair, LBT conducts its maintenance activities according to its Maintenance Department Policies & Procedures Manual. The Manual contains instructions for administration, inspections, planned, preventive maintenance activities, and unplanned repairs, and its use means comprehensive and consistent practices in the management of assets. It calls for timely inspections, which produce accurate, up-to-date information on asset conditions, and system preservation activities, which help prolong the life of assets. For fleet assets, samples of engine oil, transmission fluid and certain other fluids are collected at regular mileage intervals, and sent to a laboratory for testing. If deficiencies are found, the laboratory logs work orders through Mincom

Ellipse, a commercial off-the-shelf (COTS) application and database for tracking inventory and maintenance work activities. The records and practices according to the Manual help LBT to identify assets that need replacement or rehabilitation as early as three to five years away from the end of their useful lives.

D.3 LU Performance Reporting

Short Description: London Underground uses a performance reporting program to increase the reliability, capacity, and comfort of its services. The program involves tracking the following measures and using them to make investment decisions: Lost customer hours (LCH), the average passenger journey time, and ambience scores.

Long Description: LU, a subsidiary of Transport for London, provides rapid transit service to the greater London area and encompasses 11 rail lines over 249 miles. In 2003, LU outsourced the management of its assets to two PPP contractors and established a payment system that required performance reporting and involved financial incentives to perform. Though the PPP contracts have been discontinued, LU continues to use the performance reporting program to make investment decisions on its assets. Based upon performance according to the key measures of availability, capability, and ambience, LU decides which assets need to be renewed. For LU, availability means assets perform reliably. Asset failure can result in delays and disruptions for the customer. When service interruptions last more than two minutes, the duration counts in units called Lost Customer Hours (LCH). The value of time that customers lost is calculated on a daily basis. This value is averaged on a periodic basis (by month or quarter). In the calculations, delays during the rush hour are weighted more heavily than those that occur during the off-peak (£6/hr/person versus £4/hr/person). The calculations also consider the number of people going through the stations. This measure creates incentives for investments that improve signal reliability and reduce rolling stock failures.

The measure of capability involves the capacity of the assets to accommodate higher volumes of passengers. To determine performance according to this measure, LU calculates the average passenger journey time on each line. When trains run more frequently and faster, they reduce the journey time experienced by each customer, reduce crowding at the stations, and service more people. Line upgrade investments that allow higher speeds on tracks, build more interlockings, increase rolling stock availability, and increase the capacity of each train would improve capability. High capability can also be achieved through effective maintenance and better use of spare trains and by addressing speed restrictions.

Finally, ambience, which reflects the quality of the traveling environment, is important because customers value cleanliness and comfortable conditions. In the past, LU used mystery shopping surveys to quantify ambience; however, it plans to use performance of lighting, power, ventilation, and other subsystems at stations and trains and age profiles of assets. Investments that provide cool temperatures in the summer, keep the train seats clean, prevent littering and graffiti, and enhance ride quality would help to perform according to this measure.

D.4 MARTA Integrated Maintenance Management

Short Description: The Metropolitan Atlanta Rapid Transit Authority (MARTA) developed an integrated maintenance management system that includes an asset database with data needed to determine rehabilitation and replacement needs.

Long Description: The Metropolitan Atlanta Rapid Transit Authority (MARTA) provides 92 bus lines and 4 lines or 48 miles of heavy rail rapid transit service to the greater Atlanta area. To track its assets, MARTA used to rely on its Maintenance Management Information System (MMIS), a stand-alone database developed in-house. MMIS required many manual steps to generate reports and used varying nomenclature and fields. Consequently, much of the data was inconsistent, incomplete, or duplicated, and needed field visits to be verified. However, reliable condition information is needed to determine asset rehabilitation and replacement needs and select good projects for MARTA's CIP, the 10-year investment plan. Thus, in 2006, MARTA decided to purchase MAXIMUS, a commercial-off-the-shelf application (now called AssetWorks). A multidisciplinary team composed of maintenance, vehicles, engineering, budget and accounting, IT and operations staff worked to identify the data fields and asset categories that would populate MAXIMUS to create an easy-to-use asset information system required to support the CIP. They determined that the system should provide condition rating, life cycle priority, estimated useful life (EUL), in-service date, and installation/purchase cost. Values for the life cycle priority would be one of the following: safety critical, regulatory, operations critical, operations support, operations enhancement, operations expansion, decommissioned, and salvage. They reflect the life cycle stage and priority in which an asset should be handled, where the assets critical to safety should receive the most attention and the assets awaiting salvage are of the lowest priority. Furthermore, identifying assets to enter into the system requires undergoing the Life Cycle Asset Rehabilitation Enhancement (LCARE) process. LCARE involves taking a larger asset and breaking it down into systems, subsystems, and components until a level of granularity is reached where the EUL is homogeneous. For example, rail tracks are broken down to tangents and interlockings because tangents have longer life spans. The team decided, however, that vital relays, which are critical to safe operation of transit agency, should be treated as single records. Furthermore, to minimize data collection, the team worked to identify the asset categories where condition information is collected through existing processes. Conditions of some assets could be obtained through sampling of the Preventive Maintenance and Inspection (PMI) program. Other assets need field inspections to be assessed. In April 2010, a review of the asset database determined only 18% of the asset records had complete and full information. Staff worked to improve data quality and increased the number of records in the database from 43,000 assets to 52,000 assets. To date, 98% of records are determined to be acceptable.

D.5 MBTA State of Good Repair Database

Short Description: MBTA has developed an SGR database that its departments can use to support the inclusion of projects into the Capital Investment Program (CIP).

Long Description: MBTA, a public authority under the Massachusetts Department of Transportation (MassDOT), provides bus, rapid transit, water taxi, paratransit, and commuter rail service to the greater Boston area. It includes the oldest subway system in the United States, which commenced operations in 1897. Since the "Forward Funding" enabling act passed by the state legislature in 2000, the MBTA has been responsible for the preservation of the existing infrastructure and provision of reliable service, while the state has taken on the responsibility of system expansion. "Forward Funding" requires the MBTA to prepare an annual CIP, a rolling 5-year constrained investment plan, and use SGR as a criterion for the inclusion of projects in the CIP. To meet this requirement, the MBTA developed a Microsoft Access-based SGR database that has an inventory of its assets and approach for predicting future asset replacement needs based on expected asset lives. The system can provide hard numbers on how a project has operational impacts; reliability, which is estimated from the age and span of remaining useful life of assets; and cost-effectiveness, which is estimated from the ridership impact and the total cost.

D.6 MBTA Project Prioritization

Short Description: MBTA solicits its departments to propose capital projects, and evaluates and scores the projects based upon health, environmental, state-of-good-repair, operations impact, cost/benefit impact, and legal commitment objectives to develop its CIP.

Long Description: MBTA, a public authority under MassDOT, provides bus, rapid transit, water taxi, paratransit, and commuter rail service to the greater Boston area. It includes the oldest subway system in the United States, which commenced operations in 1897. During the annual preparation of the CIP, the rolling 5-year constrained investment plan, the Budget Department solicits MBTA staff to fill out a capital funding request form, and evaluates and scores the proposed projects based upon the following objectives: health, environmental, state-of-good-repair, operations impact, cost/benefit impact, and legal commitments. Note that safety concerns are not included in the scoring as MBTA's policy is to address safety concerns immediately. Data from the SGR database is used to score the state-of-good-repair criterion. However, final decisions on project priorities are made considering additional factors not captured in the scoring criteria, such as consideration of how investments on one asset type can affect others. For example, station work has implications for track work and vehicle procurements. In general, their discussions lead to the selection of the highest ranked projects for the CIP, but projects such as replacement of the Red and Orange Line cars, which are very significant, have not been included in past CIPs because their expense exceeds the available budget.

D.7 MTC Regional Transit Capital Inventory

Short Description: The Metropolitan Transportation Commission (MTC) uses the Regional Transit Capital Inventory (RTCI), an in-house database that tracks assets owned by transit agencies in the San Francisco Bay Area, to assist in the allocation of funding for asset replacement of those assets, and to project the system cost of maintaining those assets in a state-of-good repair.

Long Description: As the designated recipient of FTA funding for the nine-county San Francisco Bay Area, the Metropolitan Transportation Commission (MTC) oversees requests for federal funding from 22 transit agencies within its jurisdiction. Furthermore, as the Metropolitan Planning Organization (MPO) for this area, it also screens state funds to the 26 transit agencies that provide transit service in the region. The agencies comprise a large range of size and vary widely in terms of the services they operate and assets they own. To allocate limited funding to these diverse agencies using consistent measures, MTC developed the Regional Transit Capital Inventory (RTCI), a comprehensive database of the Bay Area transit assets. Phase I of the RCTI established a taxonomy for the assets and included a needs analysis tool, projected costs for asset replacement, and provided industry average life spans for each asset class based upon reports from the agencies and manufacturers. When operators request funding to rehabilitate or replace the assets, they must provide justification of why these established standards do not apply to them if the age of the asset is lower than the average for its class. To enable the agencies to use the RTCI for process improvements, MTC is currently developing Phase II of the RTCI. This version will improve data quality, cost estimates, and asset classifications and relate asset age with operating costs, failure rate for vehicles, and vehicle miles between failure through statistical curves.

The RTCI serves as the basis for projecting the cost of transit service into the Regional Transportation Plan (RTP), the 25-year transportation funding allocation plan for the nine counties in the San Francisco Bay Area. The RTP estimates funding needs to maintain transit assets for each agency according to three different scenarios on the Average Age of Assets as a Percentage of their Useful Life (AAAPUL), a measure that reflects overall asset conditions and goals to achieve state-of-good-repair. The first scenario is reducing the average age of assets to 50-percent of their useful life. The second scenario is preserving the current age distribution at 70-percent of useful life. The third scenario is achieving a reduction in the average asset age, but not to 50% of useful life.

D.8 MTC Project Prioritization

Short Description: The Metropolitan Transportation Commission (MTC) has established a set of processes and criteria for evaluating transit projects for inclusion in the Transportation Improvement Plan (TIP) and programming of FTA funds. Asset replacement projects are scored based on purpose of the asset, existing asset age, and other factors.

Long Description: As the designated recipient of FTA funding and the Metropolitan Planning Organization (MPO) for the nine-county San Francisco Bay Area, the Metropolitan Transportation Commission (MTC) is responsible for the annual preparation and endorsement of the region's Transportation Improvement Plan (TIP), which lists prioritized transit capital projects. The MTC worked cooperatively with the region's cities, counties and transit operators to determine the process to be used during the evaluation of transit projects for inclusion in the TIP and for programming of FTA Section 5307 and 5309 Fixed Guideway (FG) funding. The MTC adopted the results as Resolution No. 3908. It calls for operators to submit detailed capital programs with approval from their boards, whereupon they are screened, scored, and selected. The projects are screened for consistency with the plans of the operators' neighbors and the MTC's 25-year Regional Transportation Plan and for inclusion in the operators' own plans. The operators must also demonstrate adequate cash flow, clear project limits, intended scope of work, and project readiness. In addition, Resolution No. 3908 establishes funding ceilings by project type. Projects above the thresholds are filtered out, and the programming of a large portion of available funds to a single operator is prevented. The projects that pass through screening are then scored according to their project category. For asset replacement projects, project category descriptions prescribe criteria such as the age of asset to be replaced, characteristics of the new asset, and purpose of the asset. Some of the categories require that project funding be limited to additional caps. The highest scoring capital projects are assigned to a fund source and apportioned funding for the urbanized area in which the operators are the claimants.

D.9 NJDOT Capital Investment Strategy

Short Description: The Capital Investment Strategy (CIS) of the New Jersey Department of Transportation (NJDOT) proposes the allocation of transportation funding according to asset class for the next ten years and shows system impacts for alternative investment scenarios, with results of each scenario depicted using a set of key performance measures.

Long Description: The New Jersey Department of Transportation (NJDOT) is responsible for constructing, operating, and maintaining the state-owned multi-modal system. NJDOT owns and operates 2,300 centerline miles of roadway and 2,600 bridges. Also, NJDOT is mandated to coordinate with New Jersey Transit (NJT), New Jersey Turnpike Authority (NJTA), and the South Jersey Transportation Authority (SJTA) to annually produce its Capital Investment Strategy (CIS) per the Transportation Trust Fund Authority Act of 2000. The CIS provides transportation investment recommendations for the next 10 years for their collective assets and guides the development of the next Draft Capital Plan and Statewide Transportation Improvement Plan (STIP). The 2011-2020 CIS proposes to allocate the approximately $4.1 billion amount of transportation funding available to New Jersey, distributing this total by asset/investment category, and shows system impacts for alternative investment scenarios. Rather than producing separate strategies for each entity, NJDOT divides the agencies' combined assets into nine categories with a mission and vision statement and a set of goals, objectives, and performance measures for each. Inter-agency stakeholders participate in a vetting process to distribute the available $4.1 billion to help meet recommended investment targets for each category. For most asset categories the CIS depicts how system performance increases or decreases over time with various funding scenarios, supporting trade-off analyses between different investment strategies. The mix of condition levels and associated funding helps set appropriate targets and priorities. For categories such as bridges and pavements, NJDOT uses outcome measures such as percent of the asset in good condition. For other asset categories where it is more difficult to relate specific investments to the level of performance, such as safety and congestion, NJDOT uses output measures, such as percent of needs funded.

D.10 NYCT Performance Reporting

Short Description: New York City Transit (NYCT) publishes key performance indicators (KPIs) on its website and discusses the results during its monthly Transit Committee Meeting, when investment decisions are made.

Long Description: New York City Transit (NYCT), a subsidiary of the Metropolitan Transportation Authority (MTA), provides rapid transit and bus service to New York City, and serves approximately 200 million passengers each month. Achieving a state of good repair has been an important priority for NYCT for some time. To update the public and its stakeholders on its performance, NYCT provides a performance dashboard on its website and prepares the Operations Summary for internal review on a monthly basis. For both of these, performance is shown as a trend over a 24-month period. Key performance indicators (KPI) on the dashboard include:

- On-Time Performance
- Subway Wait Assessment (measuring actual time between train relative to the scheduled interval)
- Elevator and Escalator Availability
- Mean Distance Between Failures (subway, Staten Island Railway, bus)
- Percent of Completed Trips (bus)
- Customer Injury Rate (subways, bus)
- Collisions with Injury Rate (bus)

The Operations Summary provides systemwide and division results on each KPI for the month and as a rolling average for a 12-month period, and discusses significant trends. For measures of on-time performance, the discussions include causes of delays in service and a categorization of the delays into one of fifteen types. Based upon the information provided, NYCT executives work with stakeholders to identify candidate projects to improve the system. Measures in the summary include:

- Absolute On-Time Performance (by division)
- Controllable On-Time Performance (by division)
- Number of Delays (by type)
- Wait Assessment (by division)
- Mean Distance Between Failures (subway, Staten Island Railway)
- Percentage of Completed Trips (Staten Island Railway)
- Subway Customer Accidents and Injuries/Million Customers
- Subway Collisions, Derailments, and Fires
- Employee On-Duty Lost-Time Accidents

D.11 WSDOT Performance Reporting

Short Description: The Washington State Department of Transportation (WSDOT) publishes the Gray Notebook, a quarterly report on the state's transportation systems, programs, and agency activities, to inform its stakeholders of the system's performance.

Long Description: WSDOT publishes the Gray Notebook quarterly, to report on the performance of the state's transportation systems, programs, and agency activities. The Gray Notebook demonstrates WSDOT's progress toward achieving the six overarching transportation goals established for Washington State of preservation, safety, mobility, environment, stewardship, and economic vitality. It uses a set of performance measures approved by the governor and legislature and published by the Washington State Office of Financial Management (OFM) in the biennial Attainment Report. It also uses targets and benchmarks for those measures formulated through engineering experience. For example, in the 38th Edition, the Gray Notebook shows how WSDOT is meeting the state policy goal of preservation with the key performance measure of percentage of state bridges in fair or better structural condition. This measure captures the effect of a broad range of bridge activities and indicates conditions system-wide. The Gray Notebook also provides an inventory of all bridges and structures and categorizes them by construction methods, features, and age. Graphics show how this inventory collectively performs over a 6-year span. It also provides definitions for the terms good, fair, and poor to construct benchmarks and distinct levels of bridge performance. Finally, the Gray Notebook documents that the target is to maintain 97% of all bridges statewide at a rating of good or fair condition.

APPENDIX E

Analytical Approach Details

This appendix provides additional details concerning the analytical approach discussed in Section 5, including the formulae behind the approach. Section E.1 describes the prioritization model. Section E.2 details the vehicle model, while Sections E.3 and E.4 detailed the age-based and condition-based models, respectively.

E.1 Prioritization Model

As described in Section 5, the basic problem an agency faces in allocating a fixed budget to a set of capital projects is termed the Capital Budgeting Problem (*1*), though with an objective of maximizing utility rather than net present value. Utility may be equal to economic benefit, or it may include additional non-economic factors, as described in Section 4. Regardless of the specific factors included in a utility function, it may be expressed generically as a weighted sum of the utility from different aspects or objectives of the alternative as follows:

$$U(x) = \sum_i \beta_i u_i(x) \qquad (1)$$

where $U(x)$ is the utility for some alternative x, $u_i(x)$ is the utility corresponding to objective i, and β_i is the weight on objective i.

Obtaining an exact solution to the Capital Budgeting Problem requires formulating the problem as an integer program. However, this implies that the solution time for the problem increases exponentially as the problem size increases, meaning it can be time consuming to obtain an exact solution even for a seemingly modest-sized problem. Thus, various heuristic approaches are commonly used in the interest of reducing solution time. One such approach is to formulate the problem as a linear program, then round off the solution if it results in recommending fractional parts of a project. Easier still, if solving the problem for a single period and a single budget constraint, and if projects are independent of one another, then the optimal solution can be approximated by ranking projects in decreasing order of their utility-cost ratio and selecting projects until the budget is expended. This is the approach described in Section 5.

An appealing aspect of the heuristic approach outlined above is that it introduces a metric that can be used for prioritization, termed the prioritization index (PI) in Section 5. However, once additional constraints are introduced into the Capital Budgeting Problem, simply selecting projects in rank order may not yield an optimal solution. Below is a formulation of the problem adapted from Louch et al. (*2*) that includes constraints by type of work and work phase that one can use to obtain an optimal solution:

$$\max \sum_t \left(\frac{1}{1+i}\right)^t \sum_i \delta_{i,t} U_i \qquad (2)$$

such that

$$\forall_i \forall_t \delta_{i,t} = \begin{cases} 0 \\ 1 \end{cases} \qquad (3)$$

$$\forall_i \sum_t \delta_{i,t} \le 1 \qquad (4)$$

$$\forall_l \sum_i \sum_t \delta_{i,t} \sum_j \sum_k C_{i,j,k,l,t} \le M_l \qquad (5)$$

$$\forall_j \forall_l \sum_i \sum_t \delta_{i,t} \sum_k C_{i,j,k,l,t} \le J_{j,l} \qquad (6)$$

$$\forall_k \forall_l \sum_i \sum_t \delta_{i,t} \sum_j C_{i,j,k,l,t} \le K_{k,l} \qquad (7)$$

where

$\delta_{i,t}$ = 1 if alternative i is programmed beginning in period t, 0 otherwise

U_i = utility obtained from performing alternative i

$C_{i,j,k,l}$ = cost of performing alternative i beginning in period t for investment type j and work phase k, period l

M_l = maximum budget for period l
$J_{j,l}$ = maximum budget for investment type j, period l
$K_{k,l}$ = maximum budget for work phase k, period l

Solving for this problem yields a recommended set of project alternatives to fund that maximizes utility. Equations 3 and 4 specify that each alternative can be chosen once and only once. Equations 5, 6 and 7 are constraints on the overall budget, the budget by investment type (e.g., bus, rail), and by phase of work (e.g., design and construction), respectively. The formulation allows for different constraints, and different costs in each period. This approach can be easily extended to include additional constraints, such as bundling constraints that specify two alternatives must be selected together or not at all. Also, the integer constraint can be relaxed for projects that can be subdivided.

Given this model, the proposed approach to project prioritization can be summarized as follows:

- For each project alternative, the utility of the project should be calculated, and the rank of the project should be approximated using the utility/cost ratio (also termed PI).
- For alternative testing, or for cases where an agency has only an overall budget constraint approach the recommended approach to prioritization is to allocate funds in rank order until the budget is expended as described in Section 5.
- For prioritizing projects considering multiple periods and constraints, it is not recommended that ranks be used directly. Instead, the prioritization problem should be formulated as described in Equations 2 to 7 and solved either as an integer program, or one should approximate the solution by solving the problem as a linear program.
- If it is unfeasible to solve the prioritization problem as an optimization problem, then ranks can be used to develop an approximate solution, with projects selected in rank order within groups defined based on any constraints defined by the agency.
- In all cases, automated approaches should be used to provide insight into prioritization, but the final decision on project priorities should be left to decision makers. Even the most well-conceived model makes simplifying assumptions, and may omit key constraints and other information needed to make the best decision. Thus, automated prioritization approaches are best suited for tasks such as providing an initial solution for review by a decision maker, testing different strategies, or "filling in the blanks" to approximate what projects might be selected in the future given a set of known priorities.
- Once a set of projects has been selected or simulated as being selected, the resulting performance obtained from the set can be calculated. Determining the budget required to achieve a given performance target requires solving the problem for different budget levels, observing at each level what performance results from the specified budget.

E.2 Vehicle Model

As described in Section 5, the life cycle cost of a vehicle depends on its purchase cost, the costs of rehabilitation, energy (fuel, in the case of buses), maintenance and delay from road calls or failures. This cost may be expressed as follows:

$$LCC = CP + \sum_{t=0}^{A} \frac{(CMR_t + CME_t + CMM_t + CMD_t)AM}{(1+i)^t} \quad (8)$$

where
LCC = life cycle cost
CP = vehicle purchase cost
A = age in years at which a vehicle is assumed to be replaced
CMR_t = rehabilitation cost per vehicle mile at time t
CME_t = energy (fuel) cost per vehicle mile at time t
CMM_t = maintenance cost per vehicle mile at time t
CMD_t = delay cost per vehicle mile at time t
AM = annual vehicle mileage
i = discount rate

The equation above predicts based on accumulated mileage, but there are other variables that can influence the decision making process on when to rehabilitate and/or replace buses, including geography, weather, type of service operated and roadway congestion. The calculations described here should be performed at a fleet level, ideally with all vehicles exposed to the same set of environmental and operating conditions to control for these factors.

Ideally, the cost of rehabilitation per mile, CMR_t would be determined based on an agency's data. However, often it may be difficult to derive this cost based on available data. For buses a relationship between rehabilitation cost per vehicle mile and lifetime mileage was developed using data on the expected lives and replacement costs for individual bus components detailed in *Useful Life of Transit Buses and Vans* (*3*). Specifically, data were taken from Table F-2 for operators that carry out their major component replacements on a continuous, as-needed basis (rather than following a fixed schedule for major mid-life overhauls).

Rather than assume that the lives of components are exactly equal to their expected lives, probability distributions were used to account for the possibility that the actual lives of individual components may be much longer or shorter than their expected lives, particularly when rehabilitation is carried out on an as-needed basis. Figure E-1 shows the resulting relationship between rehabilitation cost per mile and lifetime mileage. The cost for a particular time t can be approximated using the accumulated mileage up to the corresponding year.

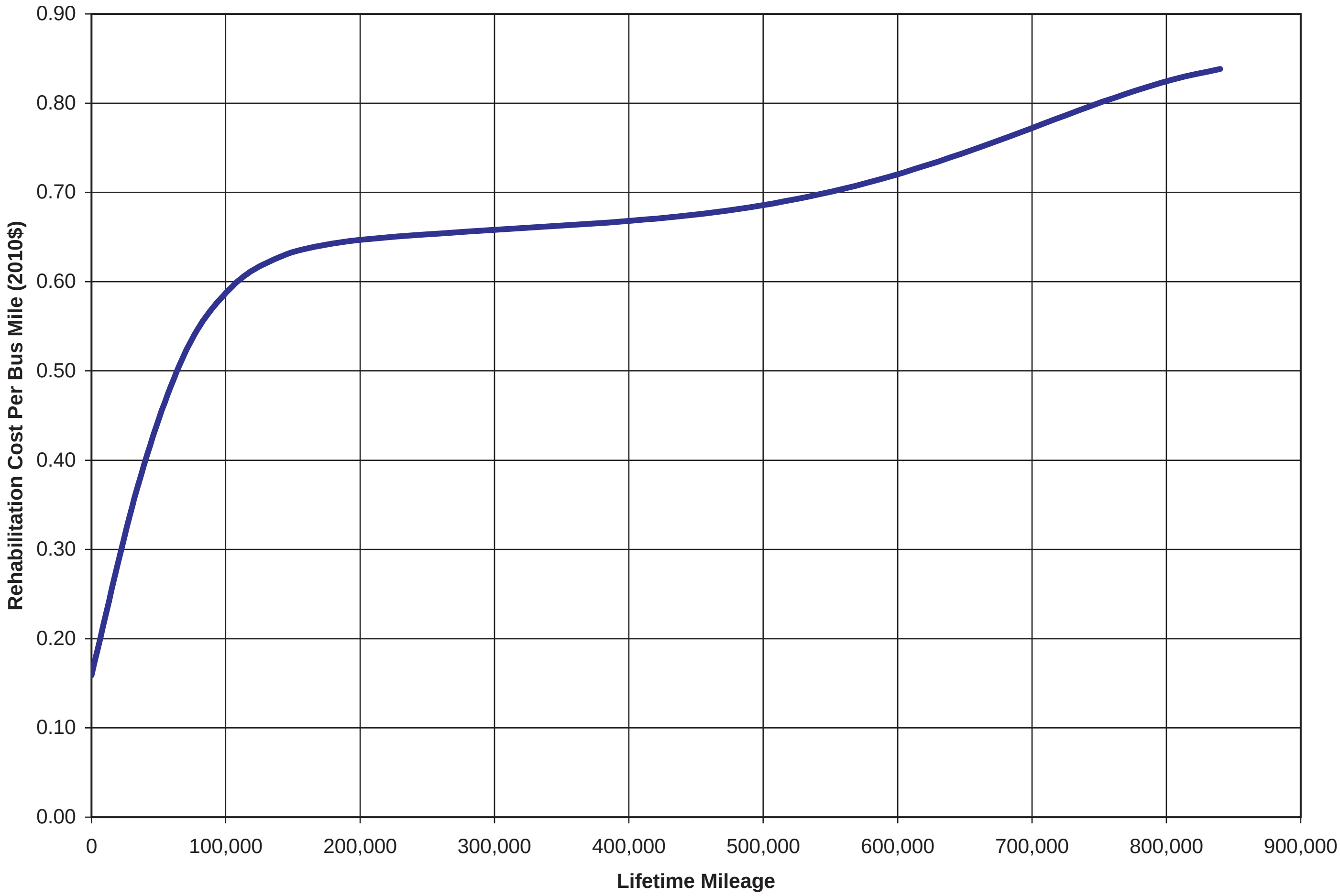

Figure E-1. Predicted bus rehabilitation cost per mile.

The following equation is used to estimate energy costs per vehicle mile as a function of lifetime mileage:

$$CME(LM) = k_{e2}e^{k_{e1} * LM} \qquad (9)$$

where

LM = lifetime mileage

k_{e1} = a constant reflecting the sensitivity of energy cost to lifetime mileage

k_{e2} = a constant set to match base year energy cost

And the following equation is used to estimate maintenance costs per vehicle mile as a function of lifetime mileage:

$$CMM(LM) = k_{m2}e^{k_{m1} * LM} \qquad (10)$$

where

k_{m1} = a constant reflecting the sensitivity of maintenance cost to lifetime mileage

k_{m2} = a constant set to match base year maintenance cost

For buses the values for the constants k_{e1} and k_{m1} were derived based on regression analyses of fuel cost per mile, maintenance cost per mile, lifetime mileage, and average speed using data from the 2009 NTD normalized to 2010 dollars. A value of 6.27E-07 was derived for k_{e1} and 1.26E-06 was derived for k_{m1}.

NTD data were used to derive constants for these values for rail, as well. The research team identified instances where rail fleets did not change from one year to the next (except, naturally, that they were one year older and had more lifetime mileage). For these fleets, energy consumption (measured in kilowatt hours) and vehicle maintenance costs were analyzed to determine how they increased from one year to the next. Regarding energy consumption, the analysis indicated that consumption increased by 2.1% per year for heavy rail and 1.6% per year for light rail. Using annual mileages per vehicle of 58,000 for heavy rail and 42,000 for light rail (per the NTD) the estimated value for k_{e1} is 4E-07 for light rail or heavy rail.

Regarding maintenance costs, the analysis indicated that maintenance costs increased by 2.2% per year for heavy rail and 2.1% per year for light rail. Using the NTD mileages this equates to values for k_{m1} of 4E-07 for heavy rail and 5E-07 for light rail.

The constants k_{e2} and k_{m2} should be set to reproduce base year values. This process is demonstrated in the supporting spreadsheet tool described in Section 5.

To predict delay costs it is necessary to first predict road calls or failures per vehicle mileage, and then relate road calls or failures to delay. The following equation is used to predict road calls or failures per vehicle mile as a function of lifetime mileage:

$$RM(LM) = k_{r2} e^{k_{r1} * LM} \tag{11}$$

where

RM = road calls or failures per vehicle mile

k_{r1} = a constant reflecting the sensitivity of road calls or failures to lifetime mileage

k_{r2} = a constant set to match base year road calls or failures

For buses the value for k_{r1} was estimated as 1.98E-06 using data on the relationship between road calls per mile and vehicle age based on data provided in *Useful Life of Transit Buses and Vans* (*3*). Vehicle age was converted to lifetime mileage assuming annual mileage of 35,000 miles. Rail analysis was performed of NTD data as described above. The analysis indicated that, on average, failures per mile increased by about 4% from one year to the next for both heavy rail and light rail. Based on the analysis values for k_{r1} were estimated to be 7E-07 for heavy rail and 1E-06 for light rail. As for fuel and maintenance costs, the constant k_{r2} should be set to reproduce base year values.

For buses, passengers delayed by a road call include those who were already on the bus at the time it went out of service and those who are waiting for the bus (up to the time when normal service is restored). Assuming that those on the bus when the road call occurs will be picked up by the next bus after the road call bus, their delay is equal to the schedule headway time. Up to the time when a replacement bus takes over the slot occupied by the road call bus, those passengers who were going to board the road call bus also are assumed to board the next bus, so their delay is also equal to the schedule headway.

The average number of passengers on the bus when the road call occurs can be estimated as passenger miles divided by revenue bus miles. We estimate the number of passengers delayed waiting for the road call bus as the product of average boardings per revenue bus hour and the recovery time, which we define as the time until a replacement bus takes over the place that should have been occupied by road call bus. Putting this all together:

$$PDR = H * VC\left(\frac{PM}{VM} + \frac{RT * PT}{VH}\right) \tag{12}$$

where

PDR = passenger delay per road call or failure

H = headway

VC = vehicles per consist (1 for buses)

PM = passenger miles

VM = revenue vehicle miles

RT = recovery time

PT = passenger trips

VH = revenue vehicle hours

As an example, assume the following for a typical bus system:

- Schedule headway (H) of 0.5 hours
- Vehicles per consist of 1
- 10 passenger miles per revenue vehicle mile (PM/VM)
- Recovery time (RT) of one hour
- 30 passenger trips per revenue vehicle hour (PT/VH)

With these assumptions, passenger delay per road call is 20 hours, calculated as $0.5 * (10.0 + 1.0 * 30.0) = 20.0$.

Explicitly modeling added delay to passenger on trains behind temporarily immobilized or slowed trains is very complicated, since this delay is very sensitive to the following:

- The fraction of rail car failures that result in immobilized or slowed trains
- The length of time the train is immobilized and the speed reduction for slowed trains
- Whether or not the train is immobilized at a location where it can be bypassed
- The time of day (with peak periods being the worst due to the shorter headways and higher passenger load factors)

Instead, we recommend that the analyst make an upward adjustment to the number of cars per train (VC) to account for this possibility. For example, if the analysis thinks that about 20% of total passenger delays due to rail car failures are experienced by passengers on trains behind an immobilized or slowed train, then a 25% upward adjustment in the number of cars per train would be appropriate. The 25% upward adjustment is calculated as 20/(100-20).

Combining Equations 11 and 12, and incorporating consideration of passenger value of time, the delay cost per vehicle mile can be calculated as a function of lifetime mileage as follows:

$$CMD(LM) = V * H * VC\left(\frac{PM}{VM} + \frac{RT * PT}{VH}\right) k_{r2} e^{k_{r1} * LM} \tag{13}$$

where V is the passenger value of time per hour. Concerning the value of time, U.S. DOT recommends that local travel time be valued at $11.20 per person-hour (in 2000 dollars) for the purpose of conducting benefit-cost analyses (*4*). This corresponds to $12.10 in 2010 dollars. However, unanticipated delays are much more onerous to travelers than recurring delays. Specifically, the literature on valuation of travel time variability suggests that, on a per hour basis, unanticipated delay is typically valued at two to six times recurring delay by travelers (5). Using the middle of this range, we assume that passenger hours of delay due to road calls or failures are valued at four time \$1.10 or \$48.40 per passenger hour.

An important consideration in the model is the appropriate point for replacing a bus, specified as *LM* in the equations above. Ideally one should set *LM* to minimize the annual cost, which may be calculated by multiplying the life cycle cost by an annualization factor as follows:

$$AC = LCC\left(\frac{i}{1-(1+i)^{-A}}\right) \quad (14)$$

where *AC* is the annual cost.

For example, with an asset life (*A*) of 10 years and discount rate (*i*) of 7%, the annualization factor is 0.1424. This means that paying a life cycle cost (*LCC*) of \$100 now is equal in value to paying \$14.24 (*AC*) at the end of each of the next 10 years.

The model can also be used to estimate the benefits of replacing vehicles older than age *A*. Specifically, the net benefit of replacing a vehicle relative to deferring the replacement can be approximated as the difference between the cost *C* of keeping the vehicle in operation an additional year and the annualized life cycle cost of a new vehicle *AC*. This difference represents the net increase in agency and user costs that would be incurred by deferring a recommended vehicle replacement for one year.

Generally, if selecting vehicles to replace, one can maximize benefits (minimize costs) by replacing vehicle when the net benefit is greater than 0. The value *C* – *AC* represents the difference between the future cost streams generated by two competing alternatives: one in which the asset is replaced now and one in which the asset is replaced at the end of this year. For the "Replace Now" alternative, the future stream of costs is equivalent to a cost of *AC* in each future year (if we assume that the replacement asset is again replaced at the end of its useful life and so on off into the indefinite future). This is because *AC* is, by definition, the annualized cost of the replacement asset. For the "Replace Next Year" alternative, the future stream of costs is *C* for this year and then *AC* for each subsequent year. Hence, the only difference between the two alternatives is their first year cost: *C* for the "Replace Next Year" alternative and *AC* for the "Replace Now" alternative.

In estimating the values of *C* and *AC* for an asset, the analyst should attempt to include all costs that are significantly affected by asset age and condition, including not only agency costs but also costs to passengers and others. Further, while there is much room for analyst discretion in selecting the cost models to be used, it is important that internally consistent procedures be used for estimating *C* and *AC*, since priorities for an asset replacement project are assigned based on their difference.

Special treatment is required when the annual cost of keeping an asset in place decreases over time. This is rare for operating, maintenance, and passenger costs. It can, however, occur for rehabilitation costs if a costly rehabilitation is required next year to keep the asset in place. In such cases, the cost of keeping the asset in place for an additional year (*C* in the above equation) should be replaced by the average cost for keeping the asset in place over the next *N* years, where *N* is selected to minimize the value of *C*. For example, if the costs required to keep the asset in place over the next five years are \$20,000, \$5,000, \$7,000, \$9,000, and \$11,000 respectively, the value of *C* is minimized when *N* equals four years. In this case, *C* is \$10,250. Note that *C* would be higher for *N* equals three or *N* equals five.

E.3 Age-Based Model

As discussed in Section 5, for the age-based model the likelihood of asset failure is modeled using a Weibull distribution. This distribution is commonly used for applications such as survival analysis, and its use is described in textbooks on applied statistics and related topics, such as (6). The mathematical formula for the cumulative probability function of this distribution is as follows:

$$f(t) = 1 - e^{-(t/\lambda)^k} \quad (15)$$

where:
- $f(t)$ = cumulative probability of asset failure;
- t = asset age (in year, miles, or other units);
- k = shape parameter; and
- λ = scale parameter.

Figure E-2 shows sample survival curves developed using Weibull distributions. These show the probability of failure on the vertical axis and asset age on the horizontal axis. The left panel shows the probability of asset failure at a given age, and the right panel shows the cumulative probability of asset failure for a given age or less.

The Weibull distribution is described by the parameters *k* and λ, which describe its shape and scale (characteristic age), respectively. The shape parameter is particularly important for determining when to replace an asset. As *k* increases the distribution shown in the left panel becomes more pronounced and failure becomes more likely over time, which tends to increase the relative benefit of replacing the asset before it reaches a specified threshold. But if $k<1$ then proactive replacement of the asset may not be justified, as the asset actually improves with age and it becomes increasingly less likely that the asset will fail as it continues to survive. The scale parameter indicates the age by which 63.2% of a population of assets is expected to fail. The shape and scale parameter were then calculated using this information and Equation 15.

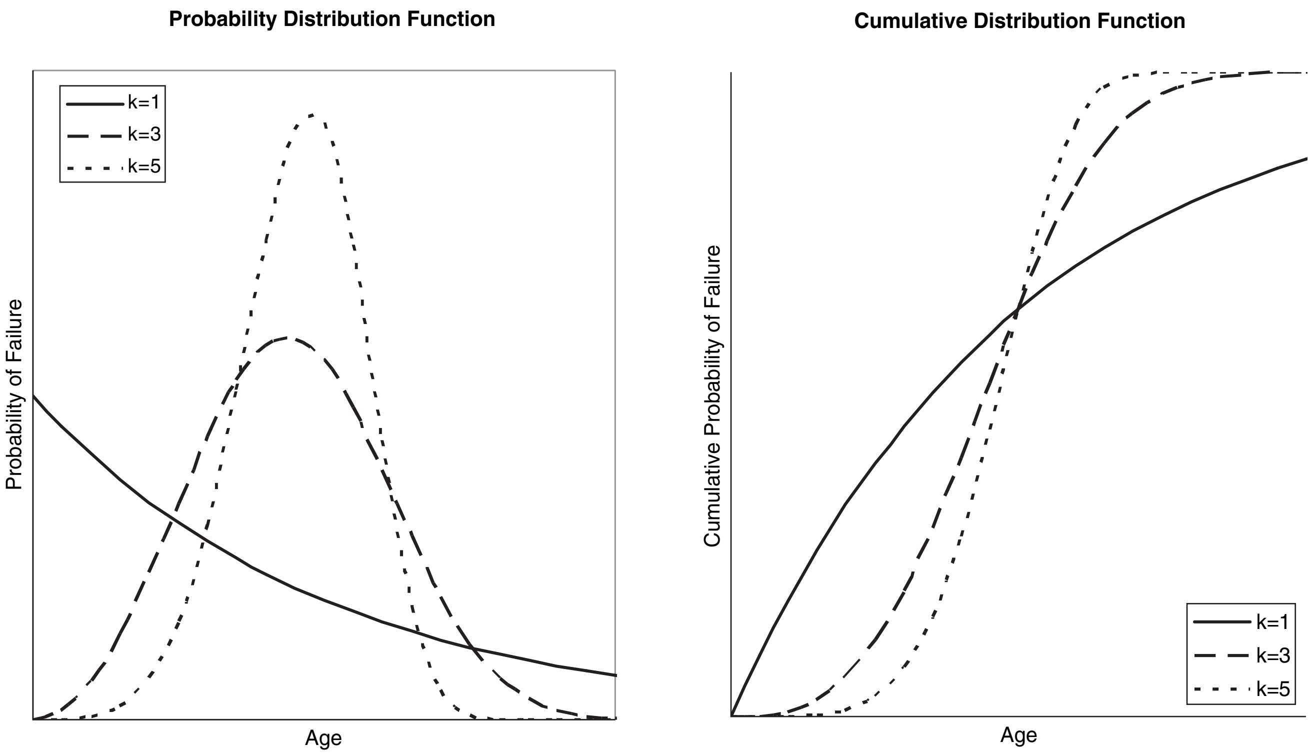

Figure E-2. Typical asset survival curves.

Note that if $k = 1$ then failure is equally likely at any time. For such assets, the determination of the optimal policy may be better determined based on the condition of the asset using a Markov Decision Process than using survival analysis, as described in the next subsection. This approach is often used for complex assets, such as bridges and facilities that have many elements or components and multiple failure modes.

A useful property of the Weibull distribution is that it can be used to predict the conditional probability of failure in time $t + 1$ given an asset has survived until time t. This conditional probability is calculated as follows:

$$P(t+1|t) = 1 - \frac{e^{-\left(\frac{t+1}{\lambda}\right)^k}}{e^{-\left(\frac{t}{\lambda}\right)^k}} \qquad (16)$$

The following approach to modeling rehabilitation and replacement analysis is recommended for assets (other than vehicles) in cases in which age is the best predictor of rehabilitation and replacement need:

- First, it is important to define what constitutes asset failure. The discussion here assumes that failure does not necessarily imply catastrophic failure of the asset, but does result in the asset's being effectively removed from service, triggering a failure cost (which may include agency and user cost components) to restore the asset to service. For instance, for an asset such as an escalator, a failure would be an interruption in service that is severe enough to trigger overhaul of the escalator. However, a minor interruption in service requiring maintenance work would not be considered a failure in this context.
- The next step is to calculate the transit agency and user costs of asset failure. Typically the cost of a failure is at least as great as the recommended action to avert failure – or if it is not then the optimal policy is to replace the asset only upon failure. The cost may include emergency costs to mobilize equipment and personnel to address the failure in the short term, and may include costs of user delay, such as to detour around a facility or asset that is out of service.
- Once asset failure and its costs have been characterized, then a survival curve should be developed for the asset. Weibull curves such as those shown in Figure 5-2, are commonly used for this application, and can be fit to data using various statistical packages.
- After a Weibull curve has been developed one can then establish the policy for replacing the asset, selecting the replacement age *A* that minimizes the annual cost *AC*. The tool described in Section 5.3 illustrates use of Monte Carlo simulation to determine these values. As in the case of the vehicle model, the marginal benefit of replacing an asset relative to deferring the replacement can be approximated as the difference between the cost of maintaining the asset an additional year and the annualized cost of a new asset

AC. The benefit of taking action relative to deferral is represented below.

$$B = P(t|t-1)*(CF - CP) + (1 - P(t|t-1))*CM - AC \quad (17)$$

where:

B = benefit of taking action relative to deferral
CF = failure cost
CM = annual maintenance cost
CP = purchase/replacement cost

The age-based modeling tool described in Section 5 is pre-populated with deterioration curves for common transit assets other than vehicles. Deterioration data from TERM Lite were used to develop these curves. To define the Weibull distribution corresponding to a TERM model, the TERM model was used to predict the age at which the predicted condition was 2.5 (assumed to be the point at which 50% of a population of assets would fail) and the age at which the predicted condition was 1.5 (assumed to be the point at which 75% of a population of assets would fail). Table E-1 details the results of this exercise, listing the asset name, corresponding ID in the TERM Lite database, and resulting shape and scale parameters for the asset's survival curve.

E.4 Condition-Based Model

The approach of using a Markov Decision Process to develop a policy for maintaining an asset is described in operations research texts (*7*), and has been used in asset management systems such as the FHWA National Bridge Investment Analysis System (*8*). The reader is referred to these resources for additional information on this approach. In formulating the problem it is necessary to describe the optimal stationary policy for the asset—that is, the optimal set of actions to take in each condition state—using Bellman's optimality equation:

$$LCC^*(x) = \min_a \left(C_{x,a} + \frac{1}{1+i} \sum_y P^a_{x,y} LCC^*(y) \right) \quad (18)$$

where

$LCC^*(x)$ = minimum life cycle cost for asset in state x
a = optimal action to perform in state x
$C_{x,a}$ = cost of taking action a in state x
$P^a_{x,y}$ = probability of transition from state x to state y given action a is performed

Although Equation 18 is a dynamic equation, it can be formulated and solved as a linear program. Once the optimal policy has been determined, the life cycle cost for an asset in state x given action a is performed in the next period can be specified as follows:

$$LCC(x|a) = C_{x,a} + \frac{1}{1+i} \sum_y P^a_{x,y} LCC^*(y) \quad (19)$$

Note this equation assumes that following the next period, the optimal policy is followed. Thus, the difference between $LCC(x|a)$ and $LCC^*(x)$ represents the additional cost incurred if action a is followed rather than the optimal action. Likewise, the benefit B of performing an action relative to deferring action for one decision period (typically one year) is the difference between the life cycle costs for the do-minimum action and the selected action.

Below are additional notes on applying this approach to transit assets:

- The approach can be easily applied to assets inspected using the five-point scale described in TERM. For complex assets, such as structures, it is generally necessary to represent the asset using subcomponents or elements, with each having its own model.
- Typically an additional "failed" state is defined, for which only one action is available. The cost of this action is the failure cost. The existence of a failure cost, if it is sufficiently high, serves to force selection of actions to avert asset failure.
- Applications of the approach typically consider agency costs only, and assume asset failure can occur only from the worst condition state. However, these assumptions tend to result in a solution in which action is deferred until an asset reaches its worst condition. Thus, if there is a probability of asset failure from states other than the worst condition, and/or if there are additional costs associated with declining condition, these should be incorporated in the model.

The condition-based modeling tool described in Section 5 is pre-populated with deterioration curves for common transit assets other than vehicles. Deterioration data from TERM Lite were used to develop these curves. The following approach was used to determine a set of transition probabilities corresponding to a given TERM model:

- An initial set of transition probabilities was defined for the "do minimum" action for condition states 2 to 5 using the TERM condition state definitions. In each state the asset could either remain in the same state or deteriorate. For States 3 to 5 it was assumed that if an asset deteriorated it would deteriorate to the next worst state (from State 5 to 4, etc . . .). For State 2 it was assumed that it was equally likely that the asset would deteriorate to State 1 or fail. The probability of deterioration for State 1 was set to be equal to that determined for State 2.
- The average condition was predicted for asset ages from 1 to 100 years using an asset starting at State 5 in Year 1.
- The Excel Solver was used to determine the set of probabilities that minimized the sum of the squares of the difference between the average condition predicted by the

TERM model and the average calculated using the transition probabilities.

The result of this process was a set of four transition probabilities for each TERM model, describing the probability of an asset remaining in State 2-5 from one year to the next. Table E-1 details the results of this exercise, listing the asset name, corresponding ID in the TERM Lite database, transition probabilities used in the condition-based model (for the "do-minimum" action).

Table E-1. Deterioration models derived from TERM data.

Asset	TERM ID	Age-Based Model Parameters		Condition Based Model – One-Year Probability of Remaining in Same State			
		Shape	Scale	5	4	3	2
Guideway-At Grade Ballasted or Expressway	10111	2.70	95.54	98.4%	96.2%	93.3%	89.0%
Guideway-Grade Crossing	10210	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Guideway-Elevated Structure	10310	2.42	100.24	98.5%	96.4%	94.1%	60.2%
Guideway-Steel Viaduct	10320	2.42	100.19	98.5%	96.4%	94.1%	60.2%
Guideway-Bridge	10330	2.70	95.54	98.4%	96.2%	93.3%	89.0%
Guideway-Foot Walk	10340	3.71	107.12	99.1%	96.9%	94.1%	90.1%
Guideway-Elevated Fill	10400	2.72	129.80	99.3%	97.1%	94.2%	90.2%
Guideway-Tunnel	10510	2.72	129.80	99.3%	97.1%	94.2%	90.2%
Guideway-Retained Cut	10600	2.72	129.80	99.3%	97.1%	94.2%	90.2%
Guideway-Tangent Direct Fixation Track	11101	3.94	48.89	96.0%	93.2%	89.2%	83.1%
Guideway-Curved Direct Fixation Track	11102	3.12	31.80	93.6%	89.4%	83.2%	73.8%
Guideway-Guarded Direct Fixation Track	11103	3.21	34.61	94.1%	90.2%	84.6%	75.9%
Guideway-Direct Fixation Tangent Platform Track	11104	2.70	39.29	94.6%	91.2%	86.1%	78.3%
Guideway-Direct Fixation Curved Platform Track	11105	2.38	29.29	92.5%	88.0%	81.3%	71.0%
Guideway-Guarded Curved Direct Fixation Track	11106	2.37	32.31	93.2%	89.1%	83.0%	73.6%
Guideway-Tangent Ballasted Track	11201	3.68	44.63	95.6%	92.5%	88.1%	81.4%
Guideway-Curved Ballasted Track	11202	3.37	37.64	94.6%	91.1%	85.9%	77.9%
Guideway-Guarded Ballasted Track	11203	3.42	40.35	95.0%	91.7%	86.8%	79.4%
Guideway-Ballasted Tangent Platform Track	11204	3.10	39.00	94.7%	91.3%	86.2%	78.5%
Guideway-Ballasted Curved Platform Track	11205	3.10	33.01	93.8%	89.7%	83.8%	74.7%
Guideway-Guarded Platform Ballasted Track	11206	4.44	63.61	97.2%	94.9%	91.6%	86.7%
Guideway-Tangent Embedded Track	11301	3.94	48.89	96.0%	93.2%	89.2%	83.1%
Guideway-Curved Embedded Track	11302	3.12	31.80	93.6%	89.4%	83.2%	73.8%
Guideway-At-Grade Crossing	11303	3.12	31.80	93.6%	89.4%	83.2%	73.8%
Guideway-Special Track Work	11400	3.33	38.03	94.7%	91.2%	86.0%	78.1%
Guideway-Direct Fixation Diamond Crossover	11402	3.16	36.09	94.3%	90.6%	85.2%	76.8%
Guideway-Direct Fixation or Ballasted Turnout	11407	3.81	46.73	95.8%	92.9%	88.7%	82.3%
Guideway-Turntable	11410	3.42	40.35	95.0%	91.7%	86.8%	79.4%
Guideway-Yard Track	11500	3.53	40.22	95.0%	91.7%	86.8%	79.4%
Guideway-Wood Tie	11601	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Guideway-Concrete Tie	11602	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Guideway-Retaining Wall	12200	1.85	49.65	95.1%	92.8%	89.1%	83.3%
Guideway-At Grade Bus	13100	3.48	30.57	98.1%	95.9%	92.9%	88.5%
Guideway-Bus Turnaround	13200	3.48	81.53	98.1%	95.9%	92.9%	88.5%

Table E-1. (Continued).

Asset	TERM ID	Age-Based Model Parameters		Condition Based Model – One-Year Probability of Remaining in Same State			
		Shape	Scale	5	4	3	2
Guideway-Elevated-Bus	13300	3.48	50.95	98.1%	95.9%	92.9%	88.5%
Guideway-Subway Bus	13500	3.48	50.95	98.1%	95.9%	92.9%	88.5%
Facilities-Administrative Building	21100	2.52	103.12	98.6%	96.4%	93.5%	89.3%
Facilities-Maintenance Building	21210	2.90	54.79	96.3%	93.7%	89.9%	84.1%
Facilities-Passenger Building	21300	2.52	103.12	98.6%	96.4%	93.5%	89.3%
Facilities-Building Utilities	21500	2.46	51.40	95.8%	93.1%	89.1%	83.0%
Facilities-Access and Parking	21509	3.48	81.56	98.1%	95.9%	92.9%	88.5%
Facilities-Building Utilities-Elevators and Conveying Systems	21510	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Facilities-Building Utilities-Generator	21512	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Facilities-Storage Yard	22210	3.48	81.56	98.1%	95.9%	92.9%	88.5%
Facilities-Storage Yard-Bus	22300	3.48	81.56	98.1%	95.9%	92.9%	88.5%
Facilities-Bus Turnaround Facility	22400	2.74	40.03	94.7%	91.3%	86.4%	78.7%
Facilities-Maintenance Equipment	23301	2.49	20.27	89.4%	82.9%	73.4%	58.7%
Facilities-Pollution Treatment	23400	3.48	30.57	98.1%	95.9%	92.9%	88.5%
Facilities-Bus Washer	23402	3.48	81.56	98.1%	95.9%	92.9%	88.5%
Facilities-Train Washer	23403	2.74	40.03	94.7%	91.3%	86.4%	78.7%
Facilities-Vehicle Paint Booth	23404	3.48	81.56	98.1%	95.9%	92.9%	88.5%
Facilities-Fuel Island	23405	3.48	81.56	98.1%	95.9%	92.9%	88.5%
Facilities-Dynamometer	23406	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Facilities-Portable Lift	23407	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Facilities-Fixed Lift	23408	3.48	81.56	98.1%	95.9%	92.9%	88.5%
Facilities-Wheel Truing Machine	23409	3.42	40.35	95.0%	91.7%	86.8%	79.4%
Facilities-Brake Lathe	23410	3.42	40.35	95.0%	91.7%	86.8%	79.4%
Facilities-Major Rail Shop	24100	3.48	81.53	98.1%	95.9%	92.9%	88.5%
Facilities-Major Bus Shop	24200	3.48	81.53	98.1%	95.9%	92.9%	88.5%
Facilities-Train Control Center	25000	3.48	50.95	98.1%	95.9%	92.9%	88.5%
Systems-Train Control, Electrification, Communications, Revenue Collection & Utilities	30001	2.80	37.00	94.3%	90.7%	85.3%	77.1%
Systems-Train Control	31001	2.50	41.34	94.8%	91.5%	86.7%	79.3%
Systems-Train Control	31101	2.74	40.03	94.7%	91.3%	86.4%	78.7%
Systems-Signals & Train Stops	31111	2.73	40.27	94.8%	91.4%	86.4%	78.8%
Systems-Train Control Cable	31121	2.77	38.75	94.6%	91.1%	85.9%	78.1%
Systems-Signal Bridge	31122	3.48	241.13	99.9%	97.7%	95.3%	79.5%
Systems-Centralized Train Control	31301	3.48	50.94	98.1%	95.9%	92.9%	88.5%
Systems-Gates, Flashers, Crossings	31400	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Roadway Traffic Signals	31410	3.48	16.31	87.9%	79.9%	68.3%	50.6%
Systems-Interlocking	31500	2.15	48.15	95.3%	92.5%	88.4%	82.1%
Systems-Electrification	32001	2.95	41.31	95.0%	91.7%	86.9%	79.5%
Systems-Electrification Catenary/Pole	32100	3.04	43.95	95.3%	92.2%	87.7%	80.7%

(continued on next page)

Table E-1. (Continued).

Asset	TERM ID	Age-Based Model Parameters		Condition Based Model – One-Year Probability of Remaining in Same State			
		Shape	Scale	5	4	3	2
Systems-Electrification Substation	32200	3.04	43.95	95.3%	92.2%	87.7%	80.7%
Systems-High Tension Towers	32213	3.48	81.56	98.1%	95.9%	92.9%	88.5%
Systems-Electrification Substation Building Components	32214	2.46	51.40	95.8%	93.1%	89.1%	83.0%
Systems-Electrification Breaker House	32300	2.17	43.94	94.8%	91.8%	87.4%	80.5%
Systems-Electrification Contact Rail/Protection Boards	32400	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Heaters	32408	2.49	20.27	89.4%	82.9%	73.4%	58.7%
Systems-Power Cable	32500	2.58	28.13	92.4%	87.7%	80.7%	69.9%
Systems-Electrical Systems	32600	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Trolley Wire	32700	3.14	65.65	97.1%	94.7%	91.4%	86.4%
Systems-Communications Cable	33100	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Communications	33102	2.49	20.27	89.4%	82.9%	73.4%	58.7%
Systems-MIS/IT/Network System	33103	3.48	15.29	87.1%	78.6%	66.3%	47.5%
Systems-Emergency Location System	33300	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-SCADA RTU	33815	3.48	5.10	74.5%	50.0%	25.0%	25.0%
Systems-Communications Hut or Room	33850	3.04	43.95	95.3%	92.2%	87.7%	80.7%
Systems-Bus On-Board Video System	33901	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Central Revenue Collection	34000	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Coin/Bill Counter	34100	3.48	5.10	74.5%	50.0%	25.0%	25.0%
Systems-Revenue Collection System-Rail	35000	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Turnstile	35104	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-In Station Revenue Collection Equipment	35116	2.49	20.27	89.4%	82.9%	73.4%	58.7%
Systems-Parking Meter	35117	3.48	15.29	87.1%	78.6%	66.3%	47.5%
Systems-Change Machine	35118	3.48	15.29	87.1%	78.6%	66.3%	47.5%
Systems-Passenger Counter-Rail	35130	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-System Utilities	36000	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Lighting	36100	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Guideway Drainage	36200	2.32	48.52	95.8%	93.1%	89.1%	83.0%
Systems-Pump Room	36202	3.48	30.57	98.1%	95.9%	92.9%	88.5%
Systems-Deep Utility Well	36203	3.14	65.65	97.1%	94.7%	91.4%	86.4%
Systems-Sump Pump/Discharge Pipes	36204	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Subway Ventilation	36301	2.32	48.52	95.8%	93.1%	89.1%	83.0%
Systems-Fan Plant	36302	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Compressed Air Pipes	36303	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Air Conditioning/HVAC-Subway	36304	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Systems-Emergency Exit	36400	3.48	50.95	98.1%	95.9%	92.9%	88.5%
Systems-Tunnel Handrail	36401	2.32	48.52	95.8%	93.1%	89.1%	83.0%
Systems-ITS, APC, AVL, CAD, GPL	37000	2.49	20.27	89.4%	82.9%	73.4%	58.7%
Station-Building-Rail	41000	2.17	43.94	94.8%	91.8%	87.4%	80.5%
Stations-Building-Subway	41250	2.72	129.80	99.3%	97.1%	94.2%	90.2%

Table E-1. (Continued).

Asset	TERM ID	Age-Based Model Parameters		Condition Based Model – One-Year Probability of Remaining in Same State			
		Shape	Scale	5	4	3	2
Stations-Shelter-Rail	41270	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Stations-Token Booth	41280	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Stations-Elevator/Escalator	41400	3.48	30.57	98.1%	95.9%	92.9%	88.5%
Stations-Parking Garage/Lot	41601	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Stations-Parking Equipment	41604	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Stations-Pedestrian Walkway/Elevated	41701	3.48	101.89	98.9%	96.7%	93.9%	89.7%
Stations-Pedestrian Walkway/Subway	41702	3.48	101.90	98.9%	96.7%	93.9%	89.7%
Stations-At-Grade Rail Platform	41801	2.22	71.25	97.1%	94.9%	91.7%	86.9%
Stations-Elevated Rail Platform	41803	2.29	80.95	97.6%	95.5%	92.4%	87.9%
Stations-Subway Rail Platform	41805	2.79	95.50	98.5%	96.3%	93.3%	89.1%
Stations-Building/Ground Access-Bus	42201	2.46	51.40	95.8%	93.1%	89.1%	83.0%
Stations-Bus Shelter	42207	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Stations-Station Canopy	42300	2.24	70.04	97.0%	94.8%	91.6%	86.7%
Stations-Bus Station Platform	42800	2.22	71.23	97.1%	94.9%	91.7%	86.9%
Stations-Signage & Graphics	42900	3.48	20.38	90.2%	83.8%	74.4%	60.1%
Stations-Ferry Terminal Building/Dock	43010	2.24	70.04	97.0%	94.8%	91.6%	86.7%

E.5 Appendix E References

(*1*) H. Weingartner, H. *Mathematical Programming and the Analysis of Capital Budgeting Problems,* Prentice Hall, 1963.

(*2*) Louch, H, Robert, W, Gurenich, D. and Hoffman, J. Asset Management Implementation Strategy. Report NJ-2009-005 prepared for the New Jersey Department of Transportation (NJDOT). NJDOT, 2009.

(*3*) Booz Allen Hamilton Inc. *Useful Life of Transit Buses and Vans.* Technical Report FTA VA-26-7229-07.1 prepared for FTA. FTA, 2007.

(*4*) Frankel, E. "Revised Departmental Guidance: Valuation of Travel Time in Economic Analysis." U.S. DOT, February 11, 2003.

(*5*) Cohen, H and Southworth, F. "On the Measurement and Valuation of Travel Time Variability Due to Incidents on Freeways." *Journal of Transportation and Statistics,* December 1999.

(*6*) Levine, D., Ramsey, P. and Smidt, R. *Applied Statistics for Engineers and Scientists,* Prentice Hall, 2001.

(*7*) Winston, W. *Operations Research: Applications and Algorithms (Third Edition),* Duxbury Press, 1994.

(*8*) Cambridge Systematics, Inc. "NBIAS 3.3 Technical Manual." Technical Report prepared for FHWA, 2007.

APPENDIX F

Additional Details on the Example Analysis

This appendix provides additional detail on the example models developed for light rail vehicles and escalators in the example presented in Section 5, as well as an alternative calculation of utility for the example. These details may be relevant for practitioners seeking to develop their own asset models.

F.1 Light Rail Vehicle Model

An important component of the vehicle model is the prediction of delay. Figure 5-10 shows data on hours of train delay. Each hour of train delay is assumed to cost $4,840 (using the default value of time of $48.40 for delay calculations and assuming an average of 100 passengers per train). It was noted that not all in-service failures result in delay, and not all delays are strictly the result of an in-service failure. However, the two are clearly correlated and over the period from 2005 to 2010 train delay per in-service failure averaged to be 16.5 minutes. Thus, the user cost of delay per failure is assumed to be approximately $1,330.

The data on in-service failures were used to develop models for each fleet for predicting failures per mile (the inverse of MDBF) as a function of accumulated mileage, as shown in Equation *11* in Appendix E. A single value of 4.56E-06 was derived for k_{r1} for both subfleets. Using this value, k_{r2} was calculated separately for each fleet to match 2010 results (8.26E-06 for Subfleet A, 6.40E-6 for Subfleet B). Table F-1 shows the accumulated mileage per vehicle by year for each subfleet, as well as the actual and predicted MDBF and failures (per million miles). For Subfleet A the accumulated mileage was assumed to be reset with completion of overhaul work in 2005.

Data on maintenance spending were used to derive a relationship between accumulated mileage and maintenance costs per mile, as shown in Equation *10* in Appendix E. A value of 4.52E-06 was derived for k_{m1} and a value of 1.54 was derived for k_{m2} based on this equation. Table F-2 summarizes the data used to derive this relationship, showing routine and heavy maintenance costs by fiscal year. The accumulated mileage shown in Table F-2 is different from that in Table F-1, as the values in Table F-2 are averaged across the two subfleets (this was done as the costs are total across the subfleets). As shown in the table, routine maintenance costs have increased over time, but heavy maintenance costs declined from 2006 to 2008 (perhaps due to changes in materials costs during this period), then fluctuated from 2008 to 2010. For the purpose of this analysis heavy maintenance costs were excluded as it was not possible to relate these to accumulated mileage.

F.2 Escalator Model

An escalator model was developed assuming characteristics of escalators similar to those described in Scarf et al. *(1)*. These include:

- Escalator maintenance is contracted out. Maintenance contracts cost $69,000 per year for a new or rehabilitated escalator (Condition State 5 or 4) or $88,000 otherwise (Condition State 3, 2 or 1).
- The amount of time an escalator is out of service in a year is correlated with its condition. A new escalator is rarely out of service. However, an escalator in good condition (State 2) may be expected to be out of service two days a year, while an escalator in poor condition can be expected to be out of service for 24 days a year (two days a month).
- Rehabilitating an escalator costs $629,000 and removes the escalator from service for eight weeks. Complete escalator replacement, which is not usually performed, costs approximately $1,700,000 and removes the escalator from service for 16 weeks.
- On average 8,900 passengers use each escalator per day. If an escalator is removed from service, passengers require an additional 30 seconds, on average, to divert to another exit or use stairs. However, for elderly and disabled passengers much more additional time may be required.
- The user cost of delay, based on the above assumptions, is estimated to range from $0 to $84,000 per year plus an

Table F-1. XYZ Transit actual and predicted light rail failures.

Fiscal Year	Accum. Mileage (per vehicle)	MDBF		Failures (per million miles)	
		Actual	Predicted	Actual	Predicted
Subfleet A					
2006	25,815	10,723	10,760	93.3	92.9
2007	49,022	10,357	9,679	96.6	103.3
2008	73,816	8,421	8,644	118.8	115.7
2009	100,155	7,147	7,666	139.9	130.4
2010	126,357	6,802	6,802	147.0	147.0
Subfleet B					
2006	93,877	9,223	10,190	108.4	98.1
2007	123,501	10,914	8,902	91.6	112.3
2008	152,733	6,878	7,791	145.4	128.4
2009	177,524	7,156	6,958	139.7	143.7
2010	200,970	6,252	6,252	159.9	159.9

additional $200,000 if the escalator is rehabilitated and $400,000 if it is replaced.

- For an escalator in excellent or good condition there is a 5% chance the escalator will deteriorate to the next worst condition from one year to the next. Otherwise there is a 10% chance of deterioration. This corresponds to a life cycle of approximately 25 years for a new escalator and 20 years for a refurbished escalator.
- If an escalator in poor condition is not rehabilitated or replaced there is a risk that it will become infeasible to continue to maintain it, requiring immediate and costly replacement.
- When escalators are rehabilitated or replaced, XYZ Transit adds the capability for Voltage Dip Ride Through (VDRT) to the escalator. This enables continued operation of the escalator when its voltage drops suddenly, reducing occurrence of sudden stops. XYZ Transit believes this feature enhances safety, but it is difficult to quantify this benefit with any precision.

Figure F-1 shows the model corresponding to the above description as specified in the condition-based modeling tool. For each condition state the table lists the actions defined, the transit agency and user costs for the action, and the transition probabilities associated with the action. Based on the inputs specified, the optimal policy for an escalator is to rehabilitate the escalator if it is in State 1 or 2, but otherwise do the minimum set of actions. Rehabilitating an escalator in State 1 has a PI of 0.19, while rehabilitating in State 2 has PI of 0 .03 relative to deferring action.

F.3 Alternate Utility Function

In the example in Section 5, the utility function used is equal to economic benefits. However, one may wish to make adjustments for benefits not calculated by the tools, such as benefits from low emissions vehicles and additional safety benefits. Also, one may wish to make further adjustments to account for perceptions of agency managers and stakeholders concerning the importance of different types of investments. Below is a utility function that could be used as an alternative to that described in the sample that incorporates these factors:

$$U = 2.0B_b + 1.5B_r + 25B_t + 5B_e + 1{,}000\delta_l + 10\delta_s \quad (20)$$

where

U = utility
B_b = net benefit of bus replacement
B_r = net benefit of rail vehicle replacement
B_t = net benefit of track replacement
B_e = net benefit of escalator rehabilitation/replacement
δ_l = 1 if the alternative increases use of low emissions vehicles, 0 otherwise
δ_s = 1 if the alternative has additional safety benefits (e.g., for escalators), 0 otherwise

Table F-2. XYZ Transit light rail maintenance spending.

Fiscal Year	Maintenance Spending ($)			Per Vehicle Values	
	Total	Heavy	Routine	Acc. Mileage	Routine Maint. ($)
2006	6,630,238	1,961,856	4,668,382	49,055	56,931
2007	6,701,311	1,894,910	4,806,401	74,454	58,615
2008	6,589,856	1,753,783	4,836,073	100,763	58,977
2009	6,532,731	1,542,534	4,990,197	126,574	60,856
2010	8,065,612	1,714,036	6,351,576	151,835	77,458

		Unit Cost		Probability of Transition to State					
State	Action	Agency	User	5-Excellent	4-Good	3-Adequate	2-Marginal	1-Poor	0-Failed
5-Excellent	0-Do Minimum	69	0	95%	5%	0%	0%	0%	0%
	1-Rehab	629	200	100%	0%	0%	0%	0%	0%
	2-Replace	1,700	400	100%	0%	0%	0%	0%	0%
4-Good	0-Do Minimum	69	7	0%	95%	5%	0%	0%	0%
	1-Rehab	629	207	0%	100%	0%	0%	0%	0%
	2-Replace	1,700	407	100%	0%	0%	0%	0%	0%
3-Adequate	0-Do Minimum	88	14	0%	0%	90%	10%	0%	0%
	1-Rehab	629	214	0%	100%	0%	0%	0%	0%
	2-Replace	1,700	414	100%	0%	0%	0%	0%	0%
2-Marginal	0-Do Minimum	88	28	0%	0%	0%	90%	5%	5%
	1-Rehab	629	228	0%	100%	0%	0%	0%	0%
	2-Replace	1,700	428	100%	0%	0%	0%	0%	0%
1-Poor	0-Do Minimum	88	84	0%	0%	0%	0%	90%	10%
	1-Rehab	629	284	0%	100%	0%	0%	0%	0%
	2-Replace	1,700	484	100%	0%	0%	0%	0%	0%
0-Failed	0-Replace	1,700	484	100%	0%	0%	0%	0%	0%

Figure F-1. Specification of the XYZ Transit escalator model in the condition-based modeling tool.

Table F-3. XYZ Transit project priority calculation.

Project	Cost ($ 000)	Utility	Utility Cost Ratio (x100)	Initial Rank	Revised Rank
Replace 24-Year Old Track	105,600	171,401	162.3	2	1
Replace 22-Year Old Track	105,600	111,653	105.7	4	2
Rehabilitate Escalators in State 1 (2 escalators)	1,258	1,178	93.7	1	3
Replace 20-Year Old Track	316,800	166,244	52.5	5	4
Rehabilitate Escalators in State 2 (2 escalators)	1,258	226	18.0	6	5
Replace Light Rail Vehicle Fleet A (54 vehicles)	189,000	30,364	16.1	3	6
Replace Bus Subfleet 3 (117 buses)	46,449	1,686	3.6	7	7

Table F-3 shows the results of the utility calculation. For each project the table shows the cost, utility, utility-cost ratio (multiplied by 100), rank calculated previously, and rank calculated based on the utility function. Comparing the initial and revised ranks, the application of the utility function has the effect of emphasizing the importance of track and escalators, while deemphasizing light rail vehicle replacements. Thus, the five highest-ranked projects are track replacement and escalator rehabilitation, whereas previously vehicle replacement had the third-highest ranking. However, as one steps forward in time, vehicle replacement projects tend to increase significantly in their utility.

F.4 Appendix F References

(*1*) Scarf, P., Dwight, R., McCusker, A. and Chan, A. "Asset Replacement for an Urban Railway Using a Modified Two-Cycle Replacement Model." In *Journal of the Operational Research Society* Vol. 58, pp. 1123–1137. Operational Research Society, 2007.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation