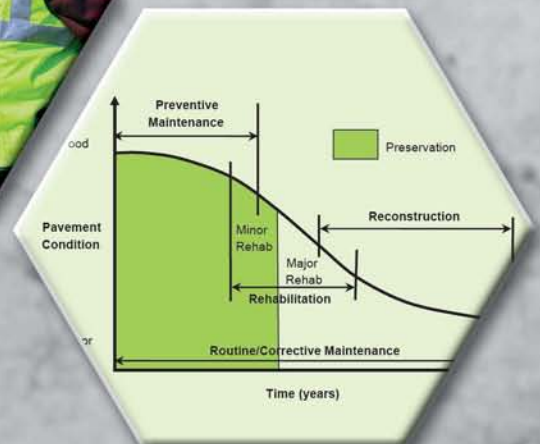
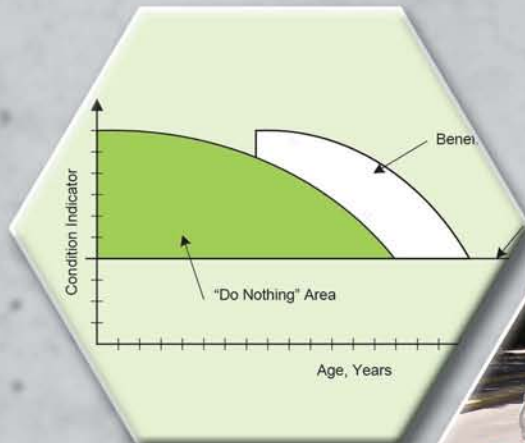


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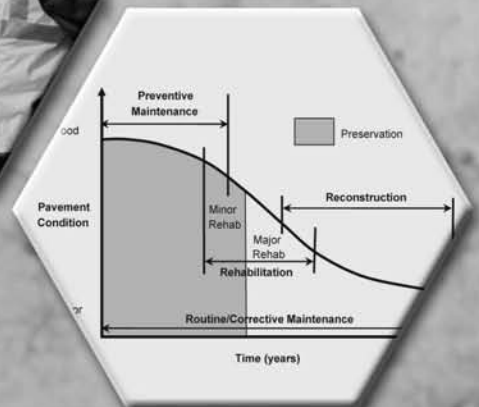
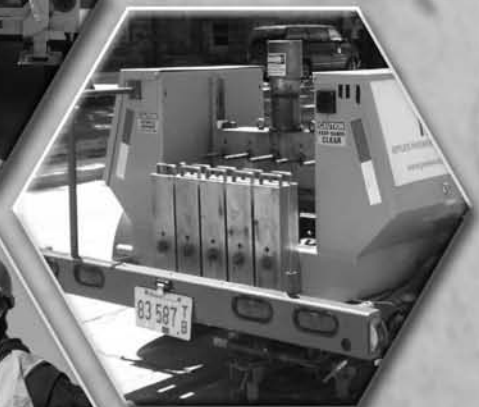
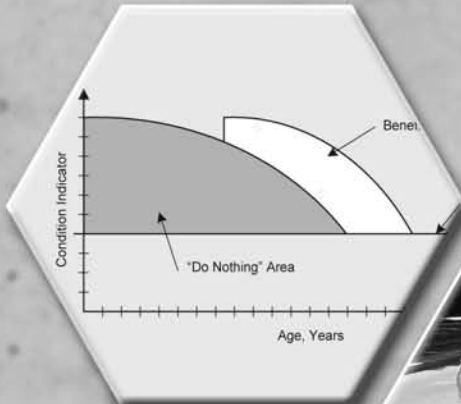
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ABSTRACT

The American Association of State Highway and Transportation Officials (AASHTO) has supported the development and use of pavement management since the early 1980s. In 1990, AASHTO published the *AASHTO Guidelines for Pavement Management Systems*, which introduced the concepts and outlined the components of a pavement management system, and documented the steps to implement a computerized system. In 2001, AASHTO published the *Pavement Management Guide*, which covered pavement management concepts in much more detail.

While many of the topics included in the 2001 *Pavement Management Guide* are still relevant today, there are several significant advancements that have taken place since its publication. For instance, there is an increased emphasis on pavement preservation programs and there are advancements that have taken place in terms of data quality and integration issues. There are also recent initiatives that are impacting the types of data required by pavement management. The increased importance of performance measurement and asset management principles will further influence the practice and future of pavement management.

EXECUTIVE SUMMARY

IMPORTANCE OF PAVEMENT MANAGEMENT

In light of an economic environment in which funding constraints force managers to do as much as possible with the dollars provided, transportation agencies have sought methods of managing their roads, bridges, and other highway assets using systematic processes based on reliable data. Defined in 1993 by the American Association of State Highway and Transportation Officials (AASHTO) as “a set of tools or methods that assist decision-makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a period of time,” pavement management has been used by federal, state, and local transportation agencies to perform the following activities:

- Assess both current and future pavement conditions.
- Estimate funding needs to achieve targeted condition levels.
- Identify pavement preservation and rehabilitation recommendations that optimize the use of available funding.
- Illustrate the consequences of different investment levels and treatment strategies on both short- and long-term pavement conditions.
- Justify and secure increased funding for pavement maintenance and rehabilitation.
- Evaluate the long-term impacts of changes in material properties, construction practices, or design procedures, or some combination thereof, on pavement performance.

The idea of managing transportation assets effectively is not new. In fact, state DOTs have been managing roads, bridges, and other highway assets since public road departments were first established in this country. Today’s agencies understand the typical life cycle of a pavement and recognize the need for periodic preservation, rehabilitation, and reconstruction activities. However, as these agencies seek ways to preserve their transportation investments, they are doing so in an environment that offers tremendous challenges from both internal and external forces. These challenges can often have long-lasting impacts on the manner in which an agency manages its transportation assets. For instance, agencies are facing severe funding reductions and pressure from elected officials and the traveling public to improve efficiency and to demonstrate that funds are being used wisely. There is increased pressure to streamline organizations and, as a result, institutional knowledge, which has been the backbone of transportation agencies for many years, is diminishing as experienced workers retire or leave government employment. There is also more competition for available funding and some agencies are responding by outsourcing or privatizing the maintenance of a portion of their network. Additionally, increased pressure for improved accountability in the use of public funds is causing agencies to establish performance-based metrics that

allow agencies to defend funding requests and to document how funds have been used and what benefits have been gained.

As a result of these pressures, stewards of transportation agencies have placed more of an emphasis on preserving their existing assets and better linking investment decisions to agency priorities and performance data. This has led to a shift in the way agencies think about asset investments, with more consideration for the interrelationship between funding decisions. This shift has fueled the development and acceptance of data-driven management as a way of preserving the investment in transportation assets. Since pavements represent one of the largest single transportation investments, the efficient management of pavements is a high priority within these agencies. As a result, pavement management has become increasingly important to address these needs.

INTRODUCTION TO THE NEW PAVEMENT MANAGEMENT GUIDE

AASHTO has supported the development and use of pavement management since the early 1980s. In 1990, AASHTO published the *AASHTO Guidelines for Pavement Management Systems* (AASHTO 1990), which introduced the concepts of pavement management, explained the differences between network- and project-level analyses, outlined the components of a pavement management system, and documented the steps to implement a computerized system. In 2001, AASHTO published the *Pavement Management Guide* (AASHTO 2001), which covered pavement management in much more detail.

This updated *Pavement Management Guide* contains the nine chapters listed below:

- Chapter 1: Introduction to the Guide
- Chapter 2: Managing Transportation Assets Effectively
- Chapter 3: Inventory Data Collection and Data Integration
- Chapter 4: Pavement Condition Assessment
- Chapter 5: Pavement Performance Modeling
- Chapter 6: Project and Treatment Selection
- Chapter 7: Using and Presenting Pavement Management Results
- Chapter 8: Implementation Activities
- Chapter 9: Future Directions

Chapters 2 through 5 provide the foundation for understanding pavement management. Chapter 2 begins with the premise that pavements are an important asset that have a significant value and represent a major investment. It emphasizes the importance of establishing a link to asset management principles by introducing the five core questions that every agency should be able to answer about its pavements, bridges, and other roadway appurtenances to manage them cost-effectively. In addition, this chapter introduces the components of a pavement management system; the use of pavement management at the project, network, and strategic levels; and the differences between the types of information used at each of the three decision levels. Finally, Chapter 2 introduces the benefits of using pavement management to support agency decisions.

Once the fundamental principles of managing assets have been established, the guide then addresses several basic pavement management components, including the establishment of an inventory and the types of data integration issues that arise when sharing data (in Chapter 3), the assessment of pavement condition (in Chapter 4), and pavement performance modeling (in Chapter 5). Chapter 3 discusses the importance of the availability and accessibility of reliable inventory and condition information for pavement management. Because of the number of sources of pavement management data, data integration and data sharing are critical to the success of pavement management. This chapter introduces several methods of integrating pavement management data, including the use of a Geographic Information System for data storage, retrieval, analysis, and presentation. The chapter also identifies strategies for managing data effectively.

Chapter 4 introduces the importance of a consistent and reliable method of assessing pavement conditions as the basis for all pavement management recommendations. The chapter introduces a variety of methods to assess the structural and functional condition of a pavement, including surface characteristics (such as pavement distress, longitudinal profile and roughness, and surface texture and friction), sub-surface characteristics, and structural evaluation. Various methods of conducting network-level pavement condition surveys are presented, and methods of developing pavement condition indices are introduced.

This chapter also presents some of the current changes that may influence the types of pavement condition data that are being collected and the frequency with which surveys are conducted. For instance, new Highway Performance Monitoring System (HPMS) reporting requirements include cracking, rutting, and faulting. The new mechanistic-empirical design procedures that have recently been developed require calibration of the performance models using pavement management data. Additionally, new technology is being developed that may influence an agency's ability to assess pavement structural condition at a network level. These, and other types of changes, are forcing agencies to periodically revisit their data collection activities to determine whether adjustments are needed to continue to meet changing agency demands.

Chapter 5 introduces some of the different methods used to develop pavement performance models that are used in pavement management to demonstrate the impact of different funding scenarios, to determine the best use of available funds, and to estimate changes in resource needs to address pavement deficiencies. Several methods of developing pavement performance methods are introduced, including deterministic, probabilistic, Bayesian, and subjective approaches. Methods of evaluating the reliability of the models are also provided.

One of the more common methods of developing pavement performance models discussed in Chapter 5 is the family modeling approach, in which condition data for pavement sections with similar characteristics are grouped together to determine a representative model to signify the typical deterioration pattern for the data set. The use of certain characteristics to group pavements into families reduces the number of variables used directly in the model (e.g., reduced to a single variable) and reduces the specificity required of the data. This simplifies the modeling process by reducing the data demands for developing the models. Since a family model represents a general performance trend for a group of pavements, the chapter also introduces a method of shifting the family performance model to predict the condition of an individual section.

Chapter 5 concludes with a discussion of the use of performance models beyond the traditional applications of pavement management. This section discusses the use of performance models to evaluate new designs and mixes, to determine the benefit of using preventive maintenance treatments, to support a forensic analysis, to estimate Remaining Service Life, and to calibrate mechanistic-empirical pavement design models.

At its most basic level, a pavement management system is used to identify and prioritize pavement preservation and rehabilitation projects. Chapter 6 introduces and illustrates methods used to develop both treatment and impact rules. The treatment rules used in pavement management describe the conditions under which a treatment is considered feasible and impact rules describe the pavement performance that might be expected following the application of a treatment. Special considerations for developing treatment rules for preventive maintenance treatments are also presented in Chapter 6.

The chapter also introduces three common methods of project and treatment selection under constrained conditions: ranking, multi-year prioritization, and optimization. A multi-year prioritization approach, which includes incremental benefit-cost and marginal cost-effectiveness analyses, is currently the most commonly used approach for project and treatment selection at the state highway level.

The chapter concludes with a discussion of the importance of coordinating pavement management with maintenance and operations, especially as pavement preservation programs increase in popularity and size. Strategies for strengthening the links between pavement management and maintenance are also provided.

Chapter 7 presents methods for using pavement management results to support agency decisions. First, it presents strategies for using pavement management results to determine pavement needs, to determine the consequences associated with different strategies, and to identify projects and treatments that make the best use of available funding. In addition, the chapter describes the use of pavement management information for allocating funding, for establishing performance targets, and for long-term planning activities. The chapter concludes with suggestions for effective use of pavement management information in presentations.

The steps involved in the implementation of a pavement management system are introduced in Chapter 8. It discusses the different types of software available and the typical steps that agencies will follow as they move forward with their pavement management implementation. The chapter also addresses some of the institutional issues that agencies face as they adopt pavement management practices and the importance of transition planning.

The guide concludes with Chapter 9, which presents a summary of some of the evolving issues that should be addressed to keep pavement management viable into the future. These issues include national initiatives in sustainability and livability that are influencing the types of data that should be considered in making pavement preservation and rehabilitation recommendations. Other considerations that are impacting pavement management, such as support for the calibration of mechanistic-empirical pavement design models and increased privatization of highway maintenance activities, are explored.

The guide's Appendices include a glossary of common terms and acronyms and a useful list of references sorted by topic area.

CHAPTER ONE



Introduction to the Guide

1.1 BACKGROUND

Pavement management provides a systematic approach to managing a pavement network that enables agencies to evaluate the consequences associated with various investment decisions and to determine the most cost-effective use of available funds for maintaining their roads, streets, and highways. Although pavement management concepts have been widely promoted since the late 1970s, the use of pavement management information to guide agency decisions is not widely employed. Technical factors, such as data quality and data integration issues, and institutional issues, such as the practice of repairing the worst roads first, have impacted the degree by which pavement management concepts have been applied in some agencies. However, pavement management is working well in a number of agencies where the recommendations from pavement management are part of an overall asset management program. In these agencies, pavement management is used to assess and justify funding needs for pavement preservation and rehabilitation, and to help set attainable pavement-related performance goals. These successes illustrate that when reliable technical information is presented effectively, it can go a long way towards overcoming the institutional issues that threaten the use of innovative and cost-effective strategies.

The American Association of State Highway and Transportation Officials (AASHTO) has supported the development and use of pavement management since the early 1980s. In 1990, AASHTO published the *AASHTO Guidelines for Pavement Management Systems* (AASHTO 1990), which introduced the concepts of pavement management, explained the differences between network- and project-level analyses, outlined the components of a pavement management system, and documented the steps to implement a computerized system. In 2001, AASHTO published the *Pavement Management Guide* (AASHTO 2001), which covered pavement management in much more detail. The following topics were included as chapter headings in the 2001 guide:

- Overview of How to Use This Guide
- Pavement Management Overview
- Selecting Pavement Management Systems Procedures
- Data Collection
- Data Management

- Data Reporting
- Predicting Deterioration
- Needs Analysis
- Selection of Candidate Sections When Funds Are Constrained
- Impact Analysis and Presenting Results to Decision Makers
- How to Implement a Pavement Management System

While many of the topics included in the guide are still relevant today, there are several significant advancements that have taken place since the guide was published. For instance, today there is more of a focus on managing pavements rather than on pavement management software. In addition, there is an increased emphasis on the use of preventive maintenance treatments as part of a pavement preservation program and there are advancements that have taken place in terms of data quality and integration issues. There are also recent initiatives that are impacting the types of data required by pavement management, including the changes to the Highway Performance Monitoring System (HPMS) and the calibration and verification activities associated with implementing the new Mechanistic Empirical Pavement Design Guide (MEPDG) (AASHTO, 2008). Other initiatives, such as the increased importance of performance measurement and asset management principles, will further influence the practice and future of pavement management. These changes also influence the need for training so practitioners can adapt.

1.2 DESCRIPTION OF THE CONTENTS

The updated *Pavement Management Guide* contains the nine chapters listed below:

- Chapter 1: Introduction to the Guide
- Chapter 2: Managing Transportation Assets Effectively
- Chapter 3: Inventory Data Collection and Data Integration
- Chapter 4: Pavement Condition Assessment
- Chapter 5: Pavement Performance Modeling
- Chapter 6: Project and Treatment Selection
- Chapter 7: Using and Presenting Pavement Management Results
- Chapter 8: Implementation Activities
- Chapter 9: Future Directions

Chapters 2 through 5 provide the foundation for understanding pavement management. Chapter 2 begins with the premise that pavements are an important asset that have a significant value and represent a major investment. For that reason, it is important that pavements are managed effectively so they provide the public with a safe and smooth method of travel as long as possible. Chapter 2 also establishes a link to asset management by introducing the five core questions that every agency should be able to answer about its pavements, bridges, and other roadway appurtenances to manage them cost-effectively. In addition, this chapter introduces the components of a pavement management system; the use of pave-

ment management at the project, network, and strategic levels; and the differences between the types of information used at each of the three decision levels. Finally, Chapter 2 introduces the benefits of using pavement management to support agency decisions.

Once the fundamental principles of managing assets have been established, the guide then addresses several basic pavement management components, including the establishment of an inventory and the types of data integration issues that arise when sharing data (in Chapter 3), the assessment of pavement condition (in Chapter 4), and pavement performance modeling (in Chapter 5).

Pavement management functions and uses are addressed in Chapters 6 and 7, which describe the project and treatment selection process (in Chapter 6) and the use and presentation of pavement management results to support agency decisions (in Chapter 7). Chapter 6 introduces the development of treatment rules for project and treatment selection, and also addresses the increased use of preventive maintenance treatments as part of a pavement preservation program. Typical uses of pavement management information are presented in Chapter 7, including its application for determining pavement maintenance and rehabilitation needs, for demonstrating the consequences of different funding strategies (e.g., *what if* scenarios), and for establishing performance targets. Chapter 7 also explores the use of pavement management information to support alternate delivery contracts and the trend towards web-based accessibility to pavement management data.

The steps involved in the implementation of pavement management are introduced in Chapter 8. This chapter addresses the needs of all types of pavement management users, from the novice agency that might need assistance with getting started or acquiring a computerized tool, to existing users who are seeking help with enhancing their existing capabilities or who are addressing critical institutional issues (e.g., resistance to change or institutional barriers) that can hinder the effective use of pavement management strategies.

The guide concludes with a summary of some of the evolving issues that should be addressed to keep pavement management viable into the future. National initiatives in sustainability and livability are already influencing the types of factors that must be considered in making pavement preservation and rehabilitation recommendations. These and other considerations that are expected to influence the way pavements are managed in the future are explored.

The guide's Appendices include a glossary of common terms and acronyms and a useful list of references sorted by topic area.

1.3 SUGGESTIONS FOR USING THE GUIDE SUCCESSFULLY

The anticipated primary audience for this guide is pavement management staff in the highway agencies. It is anticipated that most of the guide's users will view it as a resource to address particular issues or concerns that arise as agencies face the challenges associated with managing pavements effectively. The guide's organization by pavement management components and functions should help support this use.

However, the guide may also be used to assist those seeking general knowledge of pavement management concepts. Since pavement management is not a subject normally included in a civil engineering college curriculum, it is hoped that the structure of the guide will support this use as well.

The authors acknowledge that the guide was primarily developed for use by state DOTs or provincial government agencies. Even so, pavement management's fundamental concepts and principles are applicable to other types of organizations, including local agencies; regional planning agencies, such as metropolitan planning organizations (MPOs); airport authorities; and others responsible for the management of pavement networks (e.g., toll authorities, community associations, park and forest land management agencies, and corporations). The concepts are equally applicable to private and quasi-government agencies that may be managing pavements under contractual arrangements, such as public-private partnerships (PPP). Therefore, this guide could serve as a useful resource for both state DOTs and other organizations.

CHAPTER TWO



Managing Transportation Assets Effectively

2.1 IMPORTANCE OF MANAGING A PAVEMENT NETWORK EFFECTIVELY

A 2011 report estimates that the United States needs \$2 trillion dollars to repair and rebuild the nation's deteriorated roads, bridges, and other infrastructure components (ULI & Ernst & Young 2011). The magnitude of this outlay places a tremendous responsibility on asset managers to identify strategies and tools that support wise investment choices and preserve the value of their infrastructure investments as long as possible. Today, transportation agencies are looking for ways to make even more prudent decisions than in the past, using available technology as well as sound engineering and economic principles. In simple terms, agencies are seeking strategies that allow them to *get the most bang for their buck*.

As agencies seek ways to preserve their transportation investments, they are doing so in an environment that offers tremendous challenges from both internal and external forces. These challenges can often have long-lasting impacts on the manner in which an agency manages its transportation assets. For instance, agencies are facing severe funding reductions and pressure from elected officials and the traveling public to improve efficiency and to demonstrate that funds are being used wisely. There is increased pressure to streamline organizations and, as a result, institutional knowledge, which has been the backbone of transportation agencies for many years, is diminishing as experienced workers retire or leave government employment. There is also more competition for available funding and some agencies are responding by outsourcing or privatizing the maintenance of a portion of their network. Additionally, increased pressure for improved accountability in the use of public funds is causing agencies to establish performance-based metrics that allows agencies to defend funding requests and to document how funds have been used and what benefits have been gained.

The idea of managing transportation assets effectively is not new. In fact, state DOTs have been managing roads, bridges, and other highway assets since public road departments were first established in this country. Today's agencies understand the typical life cycle of a pavement and recognize the need for periodic maintenance, rehabilitation, and reconstruction activities. However, in the past, funding for maintenance and rehabilitation projects to preserve the condition of existing assets often competed with funds for more politically and publicly-driven projects that expanded the network to address capacity and mobility issues. What has changed in recent years is the inadequacy of funding to address all of the needs identified by transportation agencies. As a result, stewards of transportation agencies have placed more of an emphasis on preserving their existing assets and better linking investment decisions to agency priorities.

This has led to a shift in the way agencies think about asset investments, with more consideration for the interrelationship between funding decisions. This shift has fueled the development and acceptance of asset management principles as a way of managing transportation assets.

In most state DOTs, the pavement and bridge networks easily represent the largest single investment in transportation assets. In recognition of the tremendous value of these assets, the Government Accounting Standards Board (GASB) issued Statement 34, which recommends including the value of transportation assets in the financial statements for government agencies (FHWA 2000). As a result, since 2001, state, local, and municipal government agencies have been reporting the replacement value of transportation assets and either depreciating the asset over time, or maintaining the value through their asset management efforts. This change in reporting the value of transportation assets to preserve an agency's bonding capacity was an early factor contributing to the increased use of more effective asset management principles.

The potential impact of improving the effectiveness of investment decisions can be significant. For example, Cowe Falls et al. (1994) estimated the impact that pavement management has had on user cost savings in the Province of Alberta. Using a conservative analysis that evaluated changes in the paved network condition over a 5-year period, the authors reported that the use of pavement management software resulted in improved conditions that were converted to an increase in asset value. The study found that every dollar (Cdn) spent on pavement management in Alberta resulted in a nearly \$100 (Cdn) improvement in terms of user cost savings or savings in asset value.

The importance of adopting strategies that improve the overall effectiveness of the way in which assets are managed cannot be ignored. Whether an agency is looking for strategies to manage a single asset (e.g., pavement) or an entire network of assets, improvements that lead to wiser investment decisions can result in improved network conditions, a higher level of service for the public, a better understanding of the impact that spending in one area has in another area, and a more streamlined decision process. Coupled with the resulting improvements in accountability, the use of asset management principles (such as those described in the next section) is finding increased acceptance within state DOTs and other agencies with a significant investment in transportation assets.

2.2 INTRODUCTION TO AN ASSET MANAGEMENT APPROACH

AASHTO currently defines asset management as follows (AASHTO 2006b):

Transportation asset management (TAM) is a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their lifecycle. 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 based on several fundamental principles, which are listed below (INGENIUM 2006; NCHRP 2009).

- **Investment decisions are driven by policy.** As a result, resources are allocated based on clearly defined goals that reflect agency priorities.
- **Decisions are based on performance metrics.** Asset management includes methods for assessing agency and asset performance and for monitoring performance with time. Measures of performance should be tied to the agency strategic objectives and linked to the resource allocation process.
- **Options and trade-offs are considered in the decision process.** Investment decisions consider both the long- and short-term impacts that each option has on overall asset performance. In addition to evaluating different investment strategies within a single asset class (e.g., pavements), asset management considers investment options across asset type (e.g., more in pavements and less in bridges) and across agency objectives (e.g., asset preservation versus system expansion). The evaluation of trade-offs considers the risk associated with asset failures as well as the impact on other agency initiatives, such as sustainability or livability.
- **Decisions are based on quality information.** The type of data used to support asset management depends on the types of questions each agency needs to address and the information needed to answer the questions. The data must be credible, reliable, and maintainable over time.
- **Performance is monitored with time.** Monitoring performance provides an opportunity for agencies to track conditions and to institute processes to continue to improve performance with time.

In organizations where these principles are applied, there is a clear connection between the strategic objectives identified during the short- and long-term planning processes and the construction and maintenance programs delivered in the field. On-going monitoring activities, such as pavement condition surveys and roadside feature surveys, provide feedback to the planning process on progress towards achieving agency goals so that any necessary adjustments and corrections can be made. The relationships and connections between these activities are depicted in Figure 2-1.

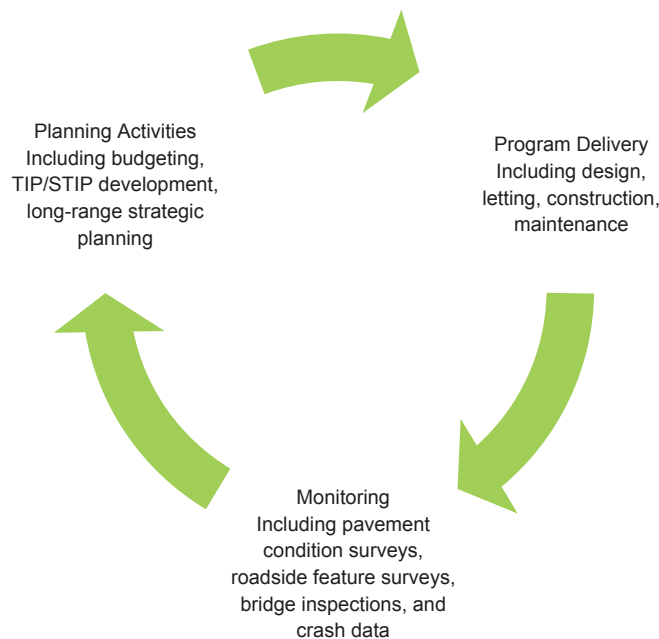


Figure 2-1. Asset Management Activity Cycle (Adapted from AASHTO 2011)

Within an asset management environment, many of the activities shown in Figure 2-1 continue to be conducted independently. However, these activities should be conducted in an environment in which there is a clear understanding of the agency's goals and objectives, and related performance measures are used at each level to guide decisions and to allocate resources. As a result, there is greater sharing of information at each level and communication across organizational functional units typically improves. Since performance expectations are well understood and accepted in an asset management environment, an agency can operate more efficiently and decisions are more streamlined.

Figure 2-2 illustrates the more streamlined decision process that exists in an asset management environment and the integration between decisions at various levels within the organization. At the strategic level, performance targets and agency goals are developed to guide the resource allocation process. Information from the network (or tactical) level supports the resource allocation decisions, as shown by the double arrows linking these activities. At the network level, decisions are made regarding funding for maintenance and operations, system preservation and renewal, and system expansion and enhancement. The impacts of different investments in each of these options are based on an analysis of each asset, using management systems (e.g., pavement management and maintenance management systems) whenever possible. At the project (or operational) level, the selected program is delivered in the field. At each level, performance measures are used to align decisions with the strategic goals.

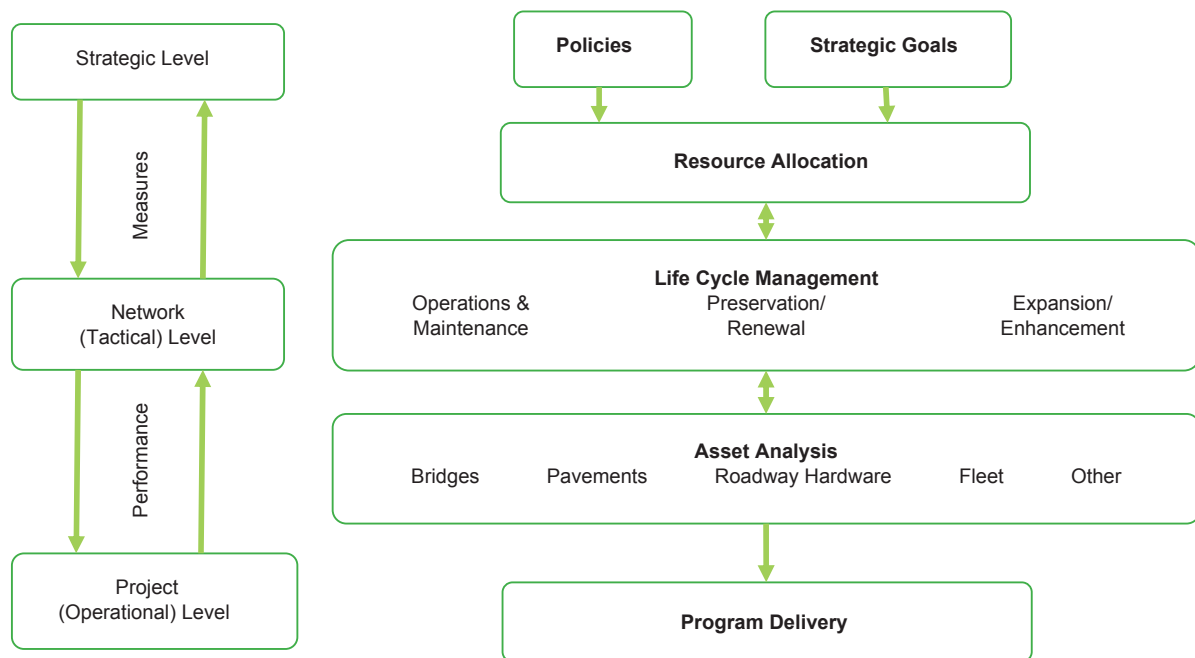


Figure 2-2. Integrated Decisions Within an Asset Management Environment

The importance of these relationships was reinforced during a recent scan tour in which representatives from the United States visited six transportation agencies in Sweden, Canada, the United Kingdom, Australia, and New Zealand. Although these agencies represented a diverse set of conditions and population densities, they agreed on the following five recommendations that will help an agency shift to an environment in which an asset management philosophy can thrive (FHWA 2010a):

1. Articulate a limited number of high-level national transportation policy goals that are linked to a clear set of measures and targets.
2. Negotiate intergovernmental agreements on how state, regional, and local agencies will achieve the national goals while translating them into local context and priorities.
3. Evaluate performance by tracking the measures and reporting them in clear language appropriate for the audience.
4. Collaborate with state, regional, and local agencies to achieve the targets by emphasizing incentives, training, and support—instead of penalties—as the preferred way to advance performance.
5. Perpetuate long-term improvements by understanding that the real value of performance management is an improved decision-making and investment process, not the achievement of many arbitrary, short-term targets.

These findings emphasize the important relationships between all levels of government to achieve national policy goals. From a state perspective, the findings support the establishment of clear goals that are linked to performance metrics and the promotion of collaborative efforts between all parties to accomplish those goals. The study also emphasized the importance of focusing on long-term improvements to reach these goals, rather than the short-term, politically influenced decisions that are often more typical in transportation agencies within the United States.

As agencies move forward to advance their adoption and implementation of an asset management framework, it is recommended that processes be adopted that enable the agency to answer the following five core questions about its assets (EPA/FHWA 2009):

- 1. What is the current state of our assets?** Answering this question requires agencies to have a good understanding of the assets they own, where they are located, and what condition they are in. The agency should also have some idea of the remaining life of each asset, and its economic value.
- 2. What is the required level of service?** Targeted levels of service for each asset are based on a number of factors, including stakeholder needs, current conditions, and anticipated funding levels. Other considerations, such as regulations (e.g., standards for retroreflectivity on signs), must also be taken into account when setting performance targets.
- 3. Which assets are critical to sustained performance?** In an asset management environment, agencies understand asset life cycles and the methods by which assets fail. This allows them to incorporate risk into the analysis by considering both the likelihood of and the potential consequences associated with failure.
- 4. What are the best investment options available?** Organizations have many options for managing their transportation assets. Within an asset management framework, agencies have the tools available to allow them to identify the investment options available and to understand the potential consequences associated with each option. Since agency goals are known, options that are not aligned with these objectives can be quickly eliminated from consideration.
- 5. From a long-term point of view, what is the best funding strategy for the agency?** Consideration of the information obtained in response to the previous questions allows an agency to make an informed decision regarding the best long-term funding strategy. Resources are allocated in alignment with this strategy and operational plans are put in place to ensure that the programs delivered support the agency's goals.

Many state DOTs have management systems in place to help answer many of the five core questions for a single asset (e.g., pavements or bridges) or an asset class (e.g., roadway hardware). These systems supply much of the information used to monitor asset performance and to evaluate the consequences of different investment strategies. These systems are critical to supporting asset management decisions. This guide focuses on one of the more commonly used management systems: pavement management.

2.3 INTRODUCTION TO PAVEMENT MANAGEMENT

AASHTO defines pavement management as “...a set of tools or methods that assist decision-makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a period of time (AASHTO 1993).” It provides a systematic approach that enables agencies to perform the following functions:

- Assess both current and future pavement conditions.
- Estimate funding needs to achieve targeted condition levels.
- Identify pavement preservation and rehabilitation recommendations that optimize the use of available funding.
- Illustrate the consequences of different investment levels and treatment strategies on both short- and long-term pavement conditions.
- Justify and secure increased funding for pavement maintenance and rehabilitation.
- Evaluate the long-term impacts of changes in material properties, construction practices, or design procedures, or some combination thereof, on pavement performance.
- Agencies that have used pavement management tools have reported improvements in the efficiency with which resources are used and better transparency when communicating with elected officials and the public (AASHTO 2001). A **pavement management system (PMS)** is the analysis tool, or software program, that is used to generate and analyze pavement management strategies.

Pavement management has evolved since the concepts were first introduced to the transportation industry in the late 1960s and early 1970s. Early pavement management activities involved the development of mathematical equations to estimate the pavement performance measurements recorded at the AASHO Road Test in Illinois. From there, researchers expanded the use of pavement management concepts by developing a “systems” approach to managing pavement performance. Most of the early pavement management systems operated on mainframe computers, which limited their application by smaller agencies.

The use of pavement management tools changed dramatically in the 1980s with the availability of personal computers. As technology has continued to evolve, pavement management practitioners have experienced dramatic changes in the way pavement condition data are collected, in the types of analyses that can be conducted, and in the methods used for sharing and reporting pavement inventory and condition information. Today, many agencies use Geographic Information Systems (GIS) as a platform for presenting pavement management results. Greater accessibility of pavement-related data through system integration has also expanded the use of pavement management information. For instance, some agencies are using their pavement condition data to correlate and calibrate sophisticated pavement design models.

In addition to changes in technology, the role of pavement management within a transportation agency has also had to evolve due to organizational, political, and societal changes that have taken place in the past 30 years. While many transportation agencies primarily focused on construction activities and system expansion when the interstate highway system was being built, today many agencies are placing a higher priority on preserving the existing system because funding levels are not adequate to address system needs. At the same time, pavement conditions are declining and agencies are having to develop more economically efficient means of maintaining their pavement network, such as the use of preventive maintenance treatments early in the life of a pavement. Additionally, agencies are developing strategies for capturing institutional knowledge before experienced personnel retire or are displaced as part of organizational restructuring. These strategies may include job shadowing, cross-training, or the development of databases, or some combination thereof, to store the historical information that will be lost. In addition, many transportation agencies are investing significant resources into integrated databases for storing and using data more effectively. Improvements in data integration have led to the availability of information to assist in making investment decisions that consider the impacts on multiple assets and the increased use of the asset management principles discussed earlier.

2.3.1 Basic Pavement Management Framework

Pavement management supports agency decisions at three different levels: strategic, network (tactical), and project (operational). Each of the three levels and the types of decisions that are made are illustrated in Table 2-1. The table also indicates the level of detail in the data used to make decisions.

2.3.1.1 Strategic Level

Strategic decisions are made at the highest level within an organization by individuals responsible for making policy and investment decisions, such as elected officials, transportation boards and commissions, city councils, and agency upper management. At this level, individuals are charged with making long-term strategic decisions that reflect agency and stakeholder priorities and establishing targeted performance levels. Traditionally, strategic decisions have been less structured than decisions made at other levels and the information on which the decisions are based is more speculative, requiring the ability to predict future conditions under a variety of scenarios. In the absence of reliable information to serve as the basis for sound business decisions, political priorities may prevail.

2.3.1.2 Network (Tactical) Level

At the **network (tactical)** level, strategies are identified to achieve the agency's goals. At this level, the overall needs of the entire road network are considered and multi-year improvement programs are developed. For pavements, several different strategies might be considered, such as a worst-first strategy in which the roads in the worst condition are the agency's highest priority and an alternate strategy in which a mix of preventive maintenance, rehabilitation, and reconstruction projects are included. The results of the network-level analysis are presented to the decision makers at the strategic level to assist them in setting realistic performance targets and to evaluate investment options. Since network-level analyses require information on the entire network, agencies strive for a balance between the level of detail that can be

provided and the resources available to collect the information. Therefore, information at the network level is generally considered to be moderate in terms of sophistication. For example, predicted condition on each individual road or street may not be exact, but overall the average rate of pavement deterioration is considered reasonable and representative. Traditionally, pavement management activities have focused primarily on network-level decisions. This guide is primarily focused on pavement management activities at the network level, but the relationship and use of pavement management information at other levels is also discussed.

Table 2-1. Differences in Strategic-, Network-, and Project-Level Decisions

Decision Level	Examples of Job Titles at this Level	Types of Decisions/Activities	Range of Assets Considered	Level of Detail	Breadth of Decisions
Strategic	• Legislator • Commissioner • Chief Engineer • Council Member	• Performance targets • Funding allocations • Pavement preservation strategy	All assets statewide	Low	Broad
Network (Tactical)	• Asset Manager • Pavement Management Engineer • District Engineer	• Project and treatment recommendations for a multi-year plan • Funding needed to achieve performance targets • Consequences of different investment strategies	A single type of asset or a range of assets in a geographic area	Moderate	Moderate
Project (Operational)	• Design Engineer • Construction Engineer • Materials Engineer • Operations Engineer	• Maintenance activities for current funding year • Pavement rehabilitation thickness design • Material type selection • Life cycle costing	Specific assets in a specific area	High	Focused

2.3.1.3 Project (Operational) Level

The third decision level is the **project (operational)** level. At this level, decisions are very specific and are usually concentrated on a particular portion of the network. For example, once a road is identified as a candidate for repair at the network level, a more detailed project-level evaluation is used to design the improvement based on in situ conditions. Project-level decisions are typically focused over a fairly short timeframe, such as the first two to three years of a five-year improvement program developed at the network level. Because a project-level analysis is concentrated on such a small portion of the network, agencies can typically afford to collect more detailed information about a pavement at this level. For instance, cores and material testing may be conducted to determine in situ conditions at the project level, but it is impractical to consider this level of detail at the network level. Individually, the impact of project-level decisions is not as far-reaching as decisions that are made at the network or strategic levels. However, over time a series of poor project-level decisions (e.g., poor design decisions) can have a cumulative negative effect on an agency's ability to meet its needs.

2.3.2 Components

Although pavement management features can vary dramatically depending on the types of information the agency needs to support decisions and the resources available, there are a few basic components that are common to most systems, as shown in Figure 2-3. The key features shown in this figure are described in the following sections.

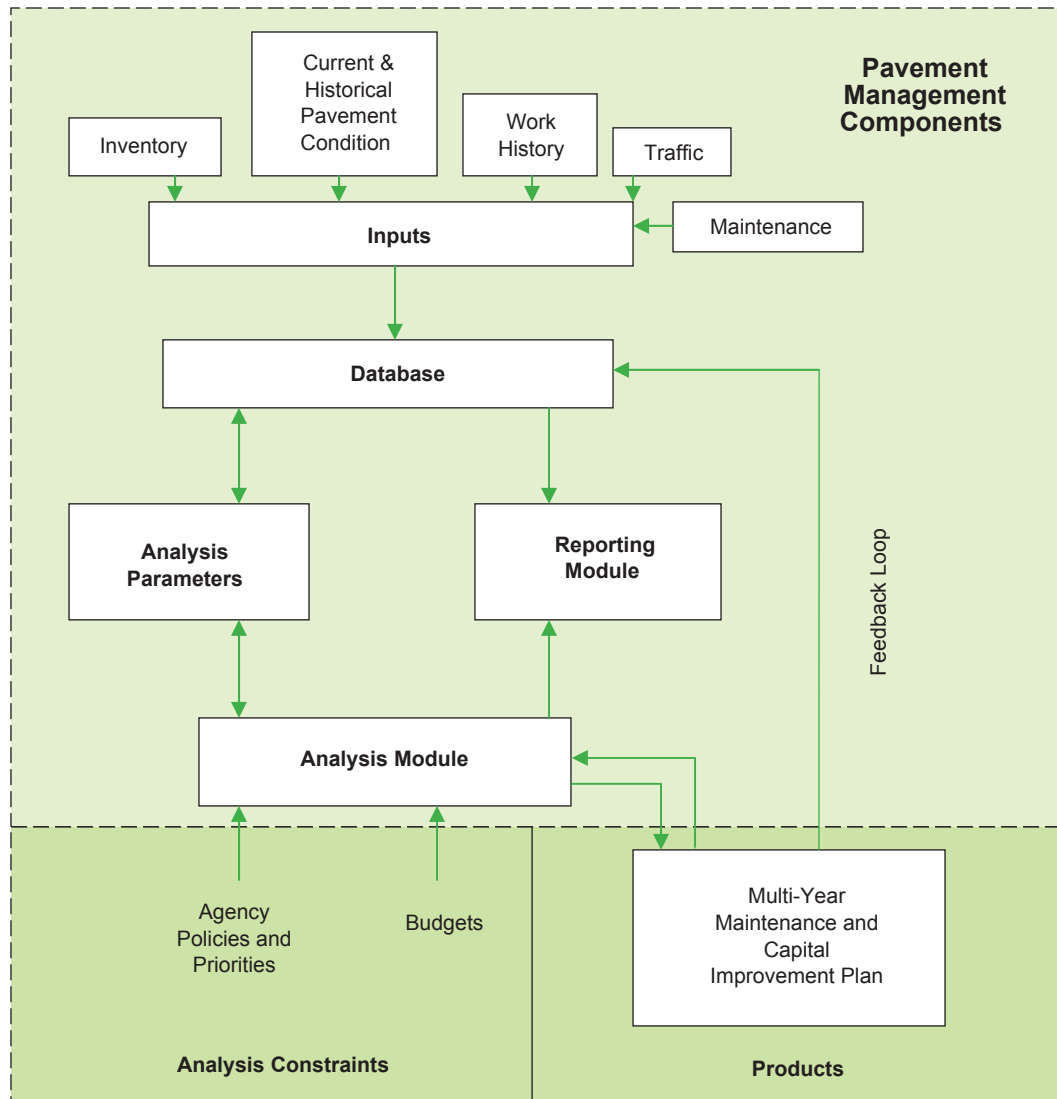


Figure 2-3. Pavement Management Components

2.3.2.1 Inputs

The foundation of any pavement management system is the data upon which all decisions are based. In the most basic pavement management systems, the inputs include general inventory information (e.g., road identifier, road location, number of lanes, lane width, pavement type) and pavement condition information (both current and historical data). In addition, a pavement management system requires an estimate of pavement age to predict future conditions. Traffic counts may be used to estimate pavement age, but it is far more common for agencies to base pavement age on the year in which the last major construction activity was performed, whether that was the original construction of the road, the date of the last resurfacing, or some other type of global treatment.

Although a pavement management system can operate with the basic information listed above, a more sophisticated analysis is possible with the inclusion of additional detailed information. For instance, if detailed construction history information is available, an agency could link differences in pavement performance to pavement structure characteristics. In the absence of detailed construction history information,

more general rates of deterioration might have to be developed. The types of inventory and condition information used in pavement management are discussed in Chapters 3 and 4, respectively.

2.3.2.2 Database

Even though pavement management activities can be performed without a formal computerized system, it helps to make use of technology for storing, sorting, and retrieving the inventory and condition information. The type of data storage can range from a simple spreadsheet to a relational, self-contained database, to a data warehouse in which all of the agency's data are stored. Other state DOTs have used their Geographic Information Systems (GIS) as a way to facilitate the shared use of data. Additional information on data storage and integration can be found in Chapter 3.

2.3.2.3 Analysis Parameters

To generate pavement project and treatment recommendations, certain analysis parameters must be created. There are at least four types of analysis parameters commonly used in pavement management: pavement deterioration models, treatment rules, impact rules, and cost models. Pavement deterioration models provide the basis for predicting future changes in network conditions. They are critical for estimating future funding needs and for determining when maintenance and rehabilitation activities will be required. The models also serve as the basis for demonstrating the consequences of different investment levels or treatment strategies so an agency can decide which option best addresses agency goals. Once models of pavement performance have been established, they can assist an agency in a number of ways. For instance, the models can be used to compare the performance of different pavement design features, to demonstrate the cost-effectiveness of different treatment strategies, or to establish treatment cycles for use in life cycle costing. The development and use of pavement performance models is described in more detail in Chapter 5.

Pavement management also relies on treatment rules to define the conditions under which pavement maintenance, rehabilitation, and reconstruction activities are considered to be feasible. Treatment rules can range in sophistication from simple rules that recommend the level of repair needed (e.g., preventive maintenance, minor rehabilitation, major rehabilitation) to very complex rules that consider many factors, such as the type of treatment last applied, the geographic location of the project, and type of traffic using the facility. The degree of sophistication for defining treatment rules depends on the needs of the agency and the availability of the data required to support treatment selection. Agencies just beginning in pavement management are cautioned to start with fairly simple decision trees and to increase the degree of sophistication over time.

In addition to developing rules for treatment selection, a pavement management system also requires that the impacts of different treatments be defined. In addition to developing rules for treatment selection, a pavement management system also requires that the impacts of different treatments be defined. These definitions are commonly referred to as impact rules, which dictate how much of an increase in pavement condition can be expected from the application of a treatment and how that treatment will perform with time. Impact rules are used in a pavement management analysis to predict consequences of various scenarios on pavement conditions. The type of software used for pavement management often determines

the degree of sophistication with which impact rules can be created. For example, some systems may assume that all treatments return a pavement to excellent condition immediately after construction and that it deteriorates at the same rate as it did prior to the construction of the treatment. However, other systems have more sophisticated capabilities that enable the user to define different impacts (e.g., one treatment may return a pavement to excellent condition while another treatment may only change crack severity from medium to low) and unique rates of deterioration for each treatment. Again, the type of computerized tool used to support pavement management frequently dictates the type of impact rules that need to be defined for each treatment.

The final component to the analysis parameters includes cost information. At a minimum, a pavement management system requires costs for each of the treatments or treatment categories considered in the analysis and anticipated budget levels for each year in the analysis.

The development and use of treatment and impact rules are discussed in Chapter 6.

2.3.2.4 Analysis Module

One of the most powerful functions of a pavement management system is its ability to quickly process and analyze pavement data to provide information that supports agency decisions regarding which projects to fund and what types of treatments to use. The pavement management analysis module is the feature that provides this type of information. As with the other features in pavement management, the degree of sophistication for the analysis can vary dramatically depending on an agency's needs. For instance, some agencies find it suitable to perform the analysis using a spreadsheet to rank different priorities. However, other agencies optimize the use of available funding over a multi-year period by using more sophisticated mathematical programming techniques such as linear programming or an incremental benefit-cost analysis. Regardless of the approach used, the primary objective of the analysis module is to assist agencies in evaluating the consequences of applying different investment levels and treatment strategies. The most common outputs from the analysis module include the following:

- An assessment of the funding level needed to reach a targeted performance level.
- Recommendations for the optimal use of available funding.
- Estimated future pavement conditions for different treatment and investment scenarios.

However, the results of an analysis can be used for many other purposes. For instance, the information can be very useful for establishing criteria for performance-based specifications or for setting performance targets under warranty contracts. More information on the techniques used to perform these activities can be found in Chapters 6 and 7. Chapter 6 presents the techniques used for project and treatment selection and Chapter 7 presents the uses of pavement management results.

2.3.2.5 Reporting Module

As the central repository for pavement-related information, a pavement management system is often the source of many different types of reports about a pavement network. Therefore, most pavement management systems have a reporting function that provides users with the ability to generate standard and ad hoc reports in many different formats. In recent years, accessibility to pavement management informa-

tion has increased dramatically through the use of GIS and web programs to obtain pavement management information. Techniques for reporting and accessing pavement management results are included in Chapter 7.

2.3.2.6 Feedback Loop

The reasonableness of the outputs from a pavement management system is largely dependent on the reliability of the inputs and the similarity between the analysis parameters and the practices in the field. Therefore, a pavement management system relies on a feedback loop that updates the pavement management records with pavement performance and construction information from the field. Ideally, the feedback loop is accomplished using automated systems that link relevant information together. In real life, the feedback loop typically relies on the relationships between agency personnel who understand the value of the information and have developed business processes to make sure the necessary information is provided on a timely basis. Examples of the types of information normally provided to pavement management through a feedback loop include maintenance and rehabilitation completion dates, changes in the conditions under which treatments are used, or changes in material properties, or some combination thereof. Pavement management can also provide feedback to other agency functions by providing information relative to the performance of different treatments under a range of conditions, the primary mechanisms causing pavement deterioration, and the average performance of various pavement designs and treatments.

2.4 TYPES OF PAVEMENT MANAGEMENT SOFTWARE

Pavement management systems can vary greatly in their complexity, flexibility, and cost. The simplest pavement management systems are public agency programs that have been developed through government funding. These types of programs typically have a standard analysis structure that is followed by all users and they are relatively low in cost. Many of the public agency developers have organized user groups and training programs to facilitate the use of their programs.

There are several very successful public agency-developed pavement management software programs. For example, the MicroPAVER pavement management system developed by the U.S. Army Corps of Engineers and distributed through the American Public Works Association (APWA) is an example of this type of software (FHWA 2008a). Another example is StreetSaver, which was developed by the Metropolitan Transportation Commission in the San Francisco Bay area (FHWA 2008a). There are also examples developed by FHWA Local Technical Assistance Programs in Utah and Michigan (FHWA 2008a). These programs are relatively inexpensive to implement and there are many private corporations that are trained to assist agencies with the implementation of these programs. Therefore, they make an excellent way for small- and medium-sized agencies to begin using pavement management tools. However, the limited ability to customize these programs to the specific needs of its users can keep some agencies from implementing these types of programs. For instance, the StreetSaver software dictates the type of pavement condition survey that is used to assess pavement condition. Consequently, an agency that collects pavement condition data using a different methodology must either change its data collection approach or select a different pavement management software program.

At the other extreme are proprietary pavement management systems developed and licensed by private corporations. These programs are typically more expensive than public domain programs, but they provide a much greater degree of flexibility in the amount of customizing that can be done for each user. For instance, while the StreetSaver program utilizes a particular pavement condition survey technique, some of the more sophisticated proprietary pavement management systems allow the user to input any type of pavement performance measure into the system. Proprietary systems typically allow users to define the types of treatments that can be analyzed, the number of budget sources that can be considered, and the way data are stored. The programs are also updated regularly by the developers so the program remains competitive with other available options. The disadvantage to the use of proprietary systems is that they are more expensive than public domain options and the number of licensed vendors who can implement and update the software is limited.

Some pavement management software vendors offer integrated packages that allow an agency to assess needs for other transportation assets (e.g., signs and sidewalks). These systems address a specific need for incorporating a broader spectrum of transportation assets in determining agency needs.

In 2008, the FHWA published a *Pavement Management Catalog* listing 12 different proprietary systems and four public agency systems from vendors who elected to participate in its development (FHWA 2008a). Information provided by the distributors of both proprietary and public domain systems is included in the *Catalog*. Although some of the information contained in the *Catalog* may be dated, the list of pavement management vendors and their contact information can be an excellent starting point for agencies interested in learning more about pavement management software. The *Catalog* also lists vendors of data collection equipment.

2.5 ROLE OF PAVEMENT MANAGEMENT IN SUPPORTING ASSET MANAGEMENT

The *Transportation Asset Management Guide: A Focus on Implementation* describes an asset management maturity scale that agencies can use to assess their current practices and to identify steps that might be taken to better adopt asset management principles (AASHTO 2011). In the early stages of the maturity scale, agencies may be collecting required data, but the use of the information in making decisions is limited. If management systems such as pavement management or bridge management are in place, the information may be used to support decisions for that class of assets only. This is commonly referred to as an “organizational silo” operation in which decisions about individual assets are made independently of other assets.

As agencies progress through the maturity scale, more structured business processes are created to support the decisions within each organizational silo to reach the performance targets established by the agency. At these levels, decisions continue to be made vertically within an organizational silo. It is not until the final stages of the maturity cycle that agencies begin to evaluate trade-offs across organizational silos so the impact of different investment levels in one asset can be evaluated in terms of the impact on other asset classes. In organizations at these levels, both vertical and horizontal decisions are being made to achieve agency performance targets. A graphical representation of the horizontal and vertical flow of information is illustrated in Figure 2-4.

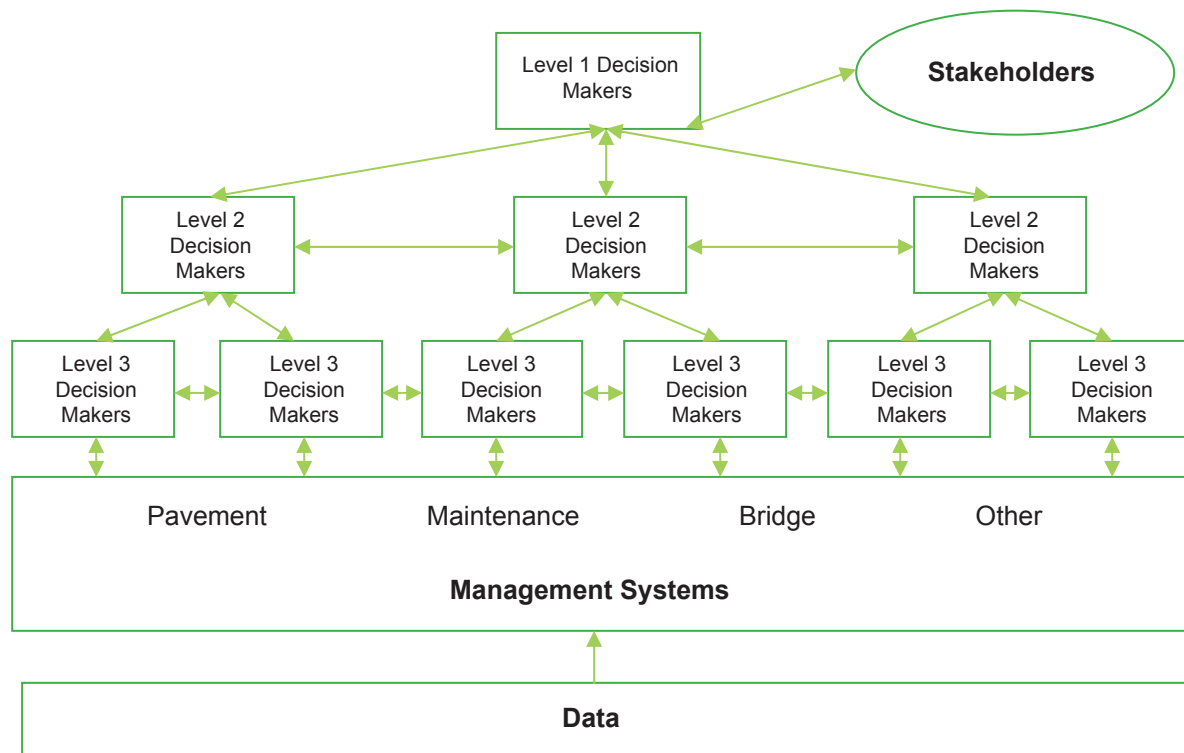


Figure 2-4. Horizontal and Vertical Flow of Information Within a Transportation Agency (Adapted from AASHTO 2011)

As shown in the figure, management systems serve as the basis for the information used to make decisions at each level. For pavements, a pavement management system provides the information needed to assess funding needs, to determine the impacts of different funding levels on pavement conditions, and to determine reasonable performance targets. Other management systems, such as bridge management or maintenance management systems, perform similar functions for other transportation assets including bridges and roadside hardware (e.g., guardrail, pavement striping), respectively. One of the responsibilities of upper-level management is to consider the information from these management systems to establish agency priorities and to allocate funds accordingly. In highly performing agencies, agency priorities and performance targets are aligned with investment decisions, and the project and treatment recommendations from the management systems are also aligned. This concept is presented graphically in Figure 2-5.

In this environment, a pavement management system has an important role in providing the answers to the five core questions introduced earlier in Section 2.2, as shown in Table 2-2. For instance, the pavement management inputs help address the first question of what the agency owns and what condition it is in. The analysis capabilities help agencies evaluate a reasonable performance target, taking into account the current network conditions and the anticipated budget levels. The performance modeling component of a pavement management system helps address the third question by simulating the various conditions under which pavements deteriorate. This helps address at least one aspect of the risk factor: the likelihood of failure. The fourth of the core questions asks what investment options are available and pavement management has a long history of providing information to address this question. The results of the analysis can be used to illustrate the consequences of different investment strategies on long-term network

conditions. This information is invaluable as agencies seek to answer the fifth core question about which funding strategy is best for the agency from a long-term point of view. Clearly, pavement management plays a critical role in asset management.

Table 2-2. Use of Pavement Management to Answer the Five Core Questions

Core Question	Pavement Management Information to Answer the Core Questions
1. What is the current state of our assets?	• Inventory • Location • Condition • Remaining service life
2. What is the required level of service?	• Forecast conditions under different financial scenarios
3. Which assets are critical to sustained performance?	• Rate of deterioration • Likelihood of failure under different financial scenarios
4. What are the best investment options available?	• Forecast conditions under different financial scenarios • Forecast conditions using different treatment strategies (e.g., fixing the worst roads first)
5. From a long-term point of view, what is the best funding strategy for the agency?	• Recommendations for funding levels and corresponding project and treatments to achieve agency goals

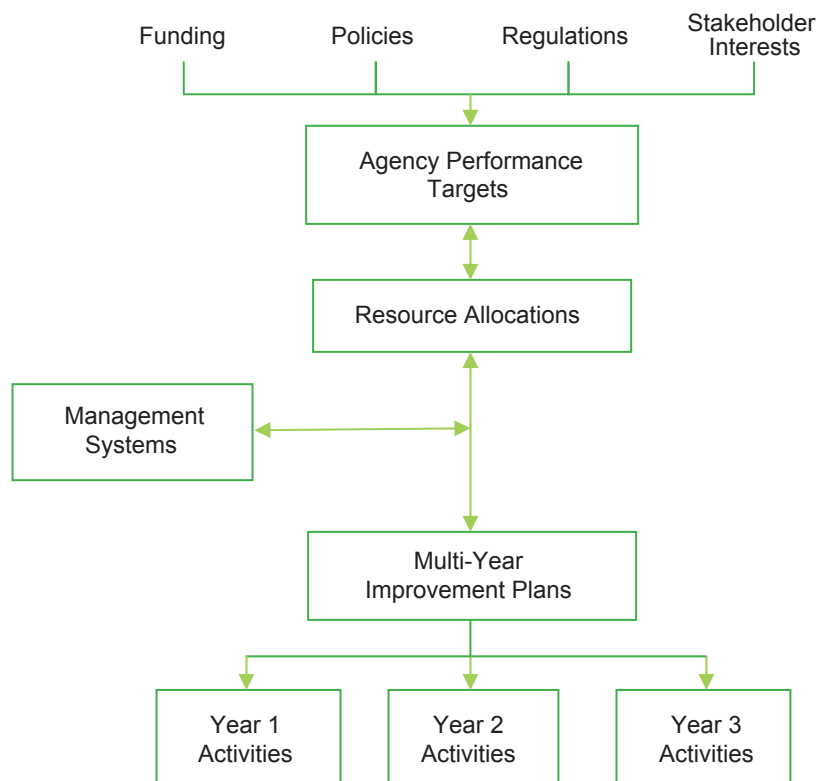


Figure 2-5. Alignment of Agency Decisions in an Asset Management Environment

2.6 BENEFITS OF USING PAVEMENT MANAGEMENT

Agencies that regularly employ pavement management concepts for managing their road network have recognized the following benefits (AASHTO 2001; FHWA 2010b):

- The identification of strategies for using available resources more effectively to improve pavement performance.
- The ability to justify and secure increased funding for pavement maintenance and rehabilitation activities.
- The ability to defend needs for pavement maintenance and rehabilitation.
- Improved access to information about the road network.
- A better sense of current and future road conditions and needs.
- The ability to identify and communicate the consequences of agency decisions on current and future pavement conditions.
- The ability to better respond to queries from both internal and external stakeholders.
- Improved transparency in decisions regarding the maintenance and rehabilitation of the pavement network.
- An improved understanding of pavement performance under different conditions.
- Improved decisions based on sound technical data.
- Better credibility with various stakeholders.
- Provides data that can be used to set performance criteria for performance specifications and warranty contracts.

For the most part, the benefits realized through the use of pavement management are relatively subjective in nature and difficult to quantify in monetary terms. However, as available resources become increasingly scarce, and transportation agencies look for methods to reduce costs, it is becoming more important to be able to quantify the benefits of pavement management to help justify the costs associated with data collection, software licenses, and personnel.

Two prominent studies have been conducted to try to quantify the benefits associated with pavement management. Hudson et al. (2000) reported that the Arizona DOT realized savings of at least \$30 for every dollar spent on the development, implementation, and operation of the pavement management software. The study found that if user costs had been considered, the savings would have increased to approximately \$250 for every dollar spent. As documented earlier in Section 2.1, Cowe Falls et al. (1994) reported that for every dollar spent on pavement management by the Province of Alberta over a five-year period, the return in terms of user cost savings or savings in asset value was nearly 100:1. In both studies, the benefits were based on improvements in pavement conditions associated with changes in the project and treatment selection process as the agencies shifted from a “worst-first” strategy to a mix of more cost-effective treatments.

2.7 CHAPTER SUMMARY

The importance of managing transportation assets effectively is a central theme throughout this chapter, which begins with an introduction to asset management and presents the philosophies upon which it is based. The five fundamental questions that every agency should be able to answer about its assets are also introduced.

Pavement management emerged in the late 1960s and early 1970s as one of the largest and most expensive assets maintained by highway agencies. This chapter introduces the concepts of pavement management and the components that are common to most pavement management systems being used today. The relationship between pavement management and asset management is also introduced, as are the benefits of the use of pavement management practices.



Inventory Data Collection and Data Integration Issues

3.1 TYPES OF INVENTORY INFORMATION NEEDED TO SUPPORT PAVEMENT MANAGEMENT

3.1.1 Basic Inventory Information

Pavement inventory data are very important features of a pavement management system given that this information identifies, classifies, and quantifies various aspects of the pavement network. To be effective, these data items must be relevant to an agency's pavement management goals and kept up-to-date as new construction projects extend the highway network or change its characteristics. Fortunately, most major pavement inventory items are well defined through industry standard descriptions, with other unique features being included on an agency by agency basis. The level of detail per inventory feature, and the ability to integrate between pavement and other roadway information, is dictated by each agency's goals and how they want to support decision making over a wide range of critical pavement responsibilities (planning, design, maintenance, and construction).

Inventory features to describe the general pavement section include the following (Khattak 2008; Dewan and Smith 2003):

- Segment beginning and end points
- Route designation along with the route type (Interstate, U.S., County, City)
- Functional classification of the road
- Segment length
- Average pavement width
- Pavement type
- Shoulder type
- Shoulder width
- Number of lanes in each traffic direction

The information listed above should be considered the minimum amount of inventory information needed to support a pavement management system. This information is typically collected by logical

pavement segments and the location of each segment is referenced through an offset to a known reference point or by Global Positioning System (GPS) coordinates.

Other pavement characteristics to be considered for inventory include:

- Layer type (e.g., HMA, portland cement concrete (PCC)).
- Layer thicknesses (all layers above subgrade).
- Layer material properties (e.g., strength, gradation).
- Joint spacing (for jointed PCC pavements).
- Transverse joint load transfer.
- Subgrade type and material classification (according to AASHTO or the United Soil Classification System (USCS)).
- Drainage information.
- Environmental or location information (e.g., region, climate factors, precipitation, freeze-thaw).
- Pavement history data (e.g., construction date, type and scope of original construction, and maintenance and rehabilitation projects).
- Cost data (e.g., construction, maintenance, or user costs, or some combination thereof).
- Ownership information (e.g., jurisdiction—state or local agency).

More detailed information may be needed to support pavement management activities for many reasons. For instance, calibrating the prediction models included in the MEPDG will require section-specific information about material properties, climate, and traffic. Additionally, establishing different treatment cost models for various geographic regions of the network will require more specific information regarding geographic location or region. Therefore, it is important that agencies evaluate the information needed to support their decision processes as they develop their pavement inventory.

3.1.2 Traffic Data Collection

Traffic volume and loading influence all phases of the pavement life cycle and are therefore essential elements of a pavement inventory. Existing and projected traffic demands influence both network- and project-level pavement management decisions. The service provided by road segments is a criterion in network-level prioritization decisions while estimates of the loads that a pavement will experience over its design life are an essential input for designing adequate pavements (Li et al. 2009). Agencies have varying traffic data needs; therefore, each agency might utilize different traffic data collection equipment, coverage, frequency, and reporting criteria. The *Traffic Monitoring Guide* prepared by the Federal Highway Administration (FHWA 2001b) provides a basic traffic data collection framework for agencies. This document provides guidance on traffic volume, vehicle classification, and truck weight monitoring. *NCHRP Report 509* entitled *Equipment for Collecting Traffic Load Data* is another good resource for use in developing or redesigning traffic monitoring programs (Hallenbeck and Weinblatt 2004). This report identifies the key issues in selecting traffic equipment and technology for collecting the truck volumes and load spectra needed for analysis and design of pavement structures.

Updated versions of the AASHTO *Guide for Design of Pavement Structures*, which is based on the equivalent single-axle load (ESAL) estimates, have been used for several decades in the United States (Banerjee et al. 2009). In this design approach, all types of expected wheel loads are converted into an ESAL, which is used as the standard traffic load input. The MEPDG proposes the use of axle load spectra instead of ESAL, which is a dramatic change for pavement design (NCHRP 2004b; Li et al. 2009). The use of axle load spectra provides a more accurate representation of the traffic loads for the design lanes. This new design approach considers load estimates by environmental condition, time (e.g., time of day and season), and vehicle classification. Typical inputs for a load spectrum are vehicle classification counts and weigh-in-motion (WIM) measurements.

The traffic data collection needs for MEPDG were addressed by another NCHRP project (Cambridge 2004). The data items that need to be collected were reported as follows:

- Short-duration classification counts (48-hour, site-specific truck volumes by class, lane, and direction-specific volumes; time of day distributions) where traffic loads will be needed.
- Long-term classification counts (e.g., collected for more than a year) at a limited number of locations around the state.
- WIM data (e.g., truck weights and counts; axle weights by type of axle such as single axle, tandem axle, tridem axle, or quad axle) collection at a limited number of locations.

These data needs are consistent with the general agency counting needs (such as the Highway Performance Monitoring System data) identified by the FHWA's *Traffic Monitoring Guide*. WIM data collection equipment collects both truck volume and load spectra but is more expensive and difficult to operate than equipment that can only count and classify vehicles (Hallenbeck and Weinblatt 2004). Therefore, agencies typically use a combination of WIM and simpler tools to collect necessary inventory data.

The types of equipment and technology available for vehicle classification counts and WIM can be categorized by the type of data collected or by whether the sensors are placed in or on the roadway surface (intrusive sensors) or whether they are placed above or beside the roadway (non-intrusive sensors) (Hallenbeck and Weinblatt 2004). While portable sensors such as road tubes, piezoelectric sensors, fiber-optic cable, portable inductance loops, and magnetometers are used for short-duration vehicle classification counts; in-place technologies, such as in-pavement sensors based on dual-inductance loops or piezoelectric cables, are more commonly used for long-duration vehicle classification counts. For WIM data, capacitance mats and BL-style piezoelectric sensors are usually preferred for short-duration; whereas permanently mounted weight sensors, such as bending plates, hydraulic load cells, piezoceramic cables, piezopolymer cables, and piezoquartz sensors, are commonly used for continuous WIM data collection.

3.1.3 Sources of Inventory Information

The information needed for pavement management within an agency typically comes from separate databases which are often maintained by different divisions. Traffic data are often collected and maintained by traffic or planning division staff, and the maintenance and rehabilitation history is typically archived by construction or maintenance division staff. An NCHRP synthesis on pavement management applications reported that only 25 percent of the road inventory data and less than 6 percent of the traffic

data, which are used in pavement management, are collected by pavement management section staff (Flintsch et al. 2004).

Spatial databases are very useful for integrating data that comes from different sources when a common location reference system is used. Although coordinate-based referencing methods are becoming popular, the majority of pavement management data are still collected using a linear referencing method, such as an offset to a known reference post (Flintsch et al. 2004). This situation hinders effective integration of different data sets and increases data redundancy. The next sections address location referencing and data integration as a means to increase the efficiency of the pavement management process.

3.2 LOCATION REFERENCING SYSTEMS (INCLUDING SEGMENTATION)

The focus of state DOTs is changing from planning, designing, constructing, and then rebuilding assets to managing the life cycle of these assets. This new focus means that DOTs are taking on the role of operating facilities, which changes their data needs and requirements to not only include facility inventory and condition assessment but also real-time operations data (traffic), incident management, and driver information systems to support decision making.

Existing location referencing systems (LRSs) at the state and local levels are almost exclusively linear and highway or street oriented. The changing role and focus of DOTs, as well as the emergence of GPS and other spatial technologies, are driving the need for an LRS that can accommodate and integrate data expressed in multiple dimensions. Transportation agencies already manage data that are referenced in one, two, and three dimensions. However, these data are usually managed in incompatible formats and are reliant on technologies and databases that cannot be integrated.

The ability to relate multiple location referencing methods for a single asset is what makes an LRS an ideal tool when integrating data among different systems to support comprehensive decision making. For example, smoothness data (IRI) are based on fixed linear segments, while friction data or falling weight deflectometer (FWD) are based on point data.

An LRS contains multiple location reference methods, each referring to assets or attributes, or both, for a single asset within their reference framework. This feature is why an LRS can serve as an ideal tool when integrating data among different systems to support comprehensive decision making. Ten core functional requirements were synthesized from the results of an NCHRP 20-27(3) workshop in an effort to form the essence of the LRS data model in dealing with processes, attributes, or both (Adams, Koncz, and Vonderohe 2001). The list below describes the core functional requirements that might impact a management system implementation:

1. Spatiotemporal Referencing Methods—A comprehensive, multidimensional LRS data model must support the processes to locate and position objects and events in three dimensions and time relative to the roadway.
2. Temporal Referencing System/Temporal Datum—A comprehensive, multidimensional LRS data model must accommodate a temporal datum that relates the database information to field locations and that also provides the domain for transforming data across temporal referencing methods. For that reason, a known time is associated with the data.

3. Transformation of Data Sets—A comprehensive, multidimensional LRS data model must support transformation among linear, nonlinear, and temporal referencing methods without loss of spatiotemporal accuracy, precision, and resolution.
4. Historical Databases—A comprehensive, multidimensional LRS data model must support re-generation of object and network states over time and maintain the network event history.
5. Object-Level Metadata—A comprehensive, multidimensional LRS data model must store and express object-level metadata to guide general data use.
6. Temporal Topology/Latency—A comprehensive, multidimensional LRS data model must support temporal relationships among objects and events and support the latency of events (e.g., the difference in time between scheduled events and actual events occurring at a particular location).
7. Various conceptual data models to represent highway and highway systems.
8. Location reference methods and location referencing systems to support highway mile post systems.
9. Reference systems to support changes or updates of the linear datum; for example, as would occur when reference points were added or deleted, or when new measures were determined between reference points and/or along an entire route.

The LRS is the foundation of a road data management system and hence the key to data integration. Any LRS, by nature, is temporal due to roadway geometrical changes such as road realignment, adding or deleting lanes, and adding or deleting road segments.

An LRS can support transformations between location referencing methods and segmentation of data. This functional requirement is a critical component to integrating data from different sources. Segmentation is the process of transforming linearly referenced data that have been stored in a table into features that can be displayed and analyzed on a map using transformation rules. For example, a transportation agency may segment a highway network by pavement type or condition. Attribute information describing characteristics specific to each highway segment can then be maintained without splitting the highway network. This process facilitates the transformation of data from different sources to defined segments or to new segments based on user requirements. Figure 3-1 shows the segmentation and transformation of data from different sources (pavement condition data in terms of IRI, traffic data in terms of average annual daily traffic (AADT), and pavement inventory data in terms of pavement type). The transformed data allow the user to assess the pavement condition based on pavement type and at the same time determine the AADT for those segments. Transformation rules should be identified for each data item so that the data can be transformed accurately and consistently every time. In this example, the IRI values are transformed based on calculating an average IRI since the IRI segment lengths are constant, while AADT is based on a weighted average by length since the segments are variable in length.

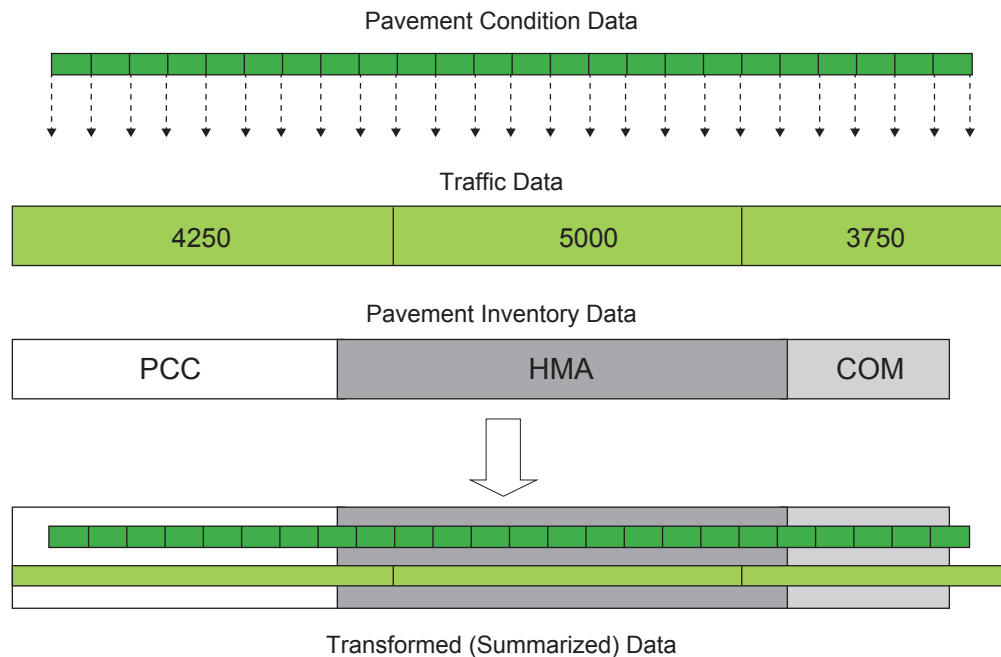


Figure 3-1. Data Transformation from Different Sources

3.3 DATA INTEGRATION APPROACHES

3.3.1 Background

Useful and reliable data are central to a fully functioning pavement management process (or any asset management system). Pavement management can be a data intensive process that involves the gathering, retrieval, storage, analysis, and communication of enormous quantities of information. The decisions that are drawn from these data are essential to the consistent, objective, and informed decision-making process underlying pavement management.

Data inputs are required to evaluate and monitor the condition and performance of the pavement asset, to maintain an asset inventory, to develop performance objectives and measures, and to identify cost-effective investment strategies. Although it is not necessary to store all of the transportation system's data in a single repository, it is critical that the data be readily accessible and comparable. Data integration and data sharing, therefore, are vital components of any management system.

FHWA defines data integration as the “process of combining or linking two or more data sets from different sources to facilitate data sharing, promote effective data gathering and analysis, and support overall information management activities in an organization” (FHWA 2001a).

In order to create the data integration process, sources of available data are considered in the context of likely needs of users. Applications are constructed that help translate the data into useable forms and formats, allowing for transformation of the information into new formats that meet those needs.

Beyond management systems, the incentives for data integration are readily apparent to organizations that collect, store, and manage disparate databases. Agencies that combine or link their multiple databases

can reduce data collection and management costs, improve the accuracy and timeliness of the information output, and support a variety of applications that draw data from various sources.

3.3.2 The Need for Integrated Data

In an organizational context, stewardship refers to management's responsibility to properly utilize and develop its resources, including its people, its property, and its financial assets. Fiscal stewardship requires a balancing of investment which is affordable and sustainable over time (Walker 2007). Asset management, like pavement management, relies heavily on highly organized and integrated databases to drive its many decision support functions. With data integration, not only can individual departments within an agency access the information needed to make informed decisions about their own assets, but the impact of their decisions on other departments is also clearer, and the potential for synergistic decision making increases.

As more and more transportation agencies implement successful management systems, the importance of data integration rises. For example, information systems used for pavement management, including design, construction, rehabilitation, and maintenance, commonly draw inputs from several data sources within an agency. Many transportation agencies have thus created effective databases and procedures for populating them. However, bringing the information from these disparate systems into a common decision-making framework exponentially increases the value of the information collected.

In an age of information, the basic benefits of information sharing are easy to imagine. In a transportation era marked by increased demand for both mobility and accountability, certain benefits advance to the forefront.

Pavement decisions are an example of an agency consideration that benefits from the availability of integrated data. For example, with proper data integration, a pavement manager can have access to the maintenance history for each pavement section, even if the information is maintained by Operations and Maintenance. Similarly, the pavement performance trends developed by pavement management can be used by field personnel to help determine the most appropriate treatment for a given set of conditions. Together, these benefits improve agency performance and provide an enhanced return on the taxpayer's investment in the agency.

Other benefits driving the adoption of data integration practices among transportation agencies include the following (FHWA 2001a):

- **Availability/Accessibility**—Asset data that are easily retrieved, viewed, queried, and analyzed by anyone within an agency encourages the integration of such data into every area of an agency that can benefit from it, spurring both innovation and better decision-making.
- **Timeliness**—Well organized data can be quickly updated; one input will often apply the data across a variety of linked systems, and the information can be time-stamped to reflect its currency.
- **Accuracy and Integrity**—Errors are greatly reduced because the integration environment drives a higher quality of input and can include automatic or convenient error-checking and verification.
- **Consistency and Clarity**—Integration requires clear and unique definition of various types of data, avoiding confusion or conflict in the meaning of terms and usage.